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ANALYSIS OF ROBOTIC AND TELEROBOTIC SYSTEMS TO PERFORM ENVIRONMENTAL REMEDIATION

DELTA RESEARCH CORPORATION
A BTG COMPANY
1501 MERCHANTS WAY
NICEVILLE FL 32578

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MATERIALS & MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR EXPEDITIONARY FORCES TECHNOLOGIES DIVISION
139 BARNES DRIVE, STE 2
TYNDALL AFB FL 32403-5323

NOTICES

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

ALLEN D. NEASE
Chief, Force Protection Branch

RANDY L. GROSS, Col, USAF, BSC
Chief, Air Expeditionary Forces Technologies Division

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Delta Research Corporation
A BTG Company
1501 Merchants Way
Niceville FL 32578

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Telerobotic and autonomous systems are becoming more common in many manufacturing and production operations. In many cases, these systems have proven to be more robust, safe, efficient, accurate, and productive than conventional human-operated (UXO) removal, mine counter-measures, lane clearance, and contaminated soil remediation, have traditionally exposed workers to hazardous and/or potentially dangerous conditions. Furthermore, worker productivity and efficiency are seriously degraded due to encumbrances from protective gear and required safety measures. Telerobotic and autonomous systems remove workers from the hazardous zone, enabling them to perform their tasks safely and efficiently. Substantial mission cost savings can also be realized through increased productivity and the extended operational hours that are possible with automated systems.

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1.0 Introduction

Telerobotic and autonomous systems are becoming more common in many manufacturing and production operations. In many cases, these systems have proven to be more robust, safe, efficient, accurate, and productive than conventional human-operated processes. Environmental restoration activities, such as unexploded ordnance (UXO) removal, mine counter-measures, lane clearance, and contaminated soil remediation, have traditionally exposed workers to hazardous and/or potentially dangerous conditions. Furthermore, worker productivity and efficiency are seriously degraded due to encumbrances from protective gear and required safety measures. Telerobotic and autonomous systems remove workers from the hazardous zone, enabling them to perform their tasks safely and efficiently. Substantial mission cost savings can also be realized through increased productivity and the extended operational hours that are possible with automated systems.

Military forces encounter multiple missions and scenarios in which personnel must operate construction equipment under hazardous conditions. Operations that occur under hazardous conditions include, but are not limited to, mine clearance, removal of UXO, and removal and remediation of hazardous waste. Personnel operating under such hazardous conditions are at risk of personal injury, illness, or death. The Air Force Wright Laboratory/Air Base Technology Branch at Tyndall AFB, Florida has a long, successful history of developing telerobotic and autonomous construction equipment for rapid runway construction and repair. Research at Wright Laboratory concentrates on telerobotic search operations; vehicle navigation, guidance and control; remote communications and global positioning links; automated damage assessment; automated target location, identification, and recognition; end effector and manipulator integration; and commercial off-the-shelf applications and associated computer environments.

To determine the applicability of telerobotic and autonomous equipment in environmental applications and to quantify the potential cost savings, a study was initiated by Wright Laboratory. This study included analyses of the feasibility, productivity, and cost effectiveness of telerobotic and autonomous construction equipment in area clearance, UXO removal, and hazardous waste removal applications. Research was conducted jointly by the Georgia Institute of Technology, School of Civil and Environmental Engineering, and Delta Research Corporation (Delta). The goals of the research were to compare traditional, human-operated systems with telerobotic and autonomous systems in environmental applications to identify break-even points, determine operational scenarios, determine economically feasible uses of construction robots for environmental cleanup, and provide a set of guidelines for developing robotic equipment more economically in the future.

During the course of the study, the Remedial Action Cost Engineering and Requirements (*RACER*) system was used to develop cost estimates for conventional, telerobotic, and autonomous operations in area clearance, UXO removal, and hazardous waste removal applications. The *RACER* cost estimates aided in determining the feasibility, productivity, and costs/benefits of the telerobotic and autonomous systems developed by the Wright Laboratory for the various operational scenarios. The operational scenarios were defined to evaluate manned, telerobotic, and autonomous modes of operation in accordance with the standard operating procedures of the mission activities. Algorithms within the *RACER* cost models were modified to reflect cost and performance data for the telerobotic and autonomous systems.

2.0 Notional Analysis Methodology

For this study, a notional analysis methodology was used to evaluate the cost effectiveness of autonomous and teleoperated equipment and to establish the relationships between certain aspects of equipment design and the corresponding cost. This methodology follows the classic scientific approach. First, a hypothesis or notion was developed to explain an observation, concept, or idea. Next, the notion was tested to determine its validity. If the notion was not valid, it was modified and retested. If the notion was valid, then it was characterized. This characterization can be defined by quantitative or qualitative relationships, or both.

The quantitative relationships are determined by first conducting sensitivity analyses to bound site conditions, and then using a parametric analysis tool to quantify system performance. Fuzzy logic is used to evaluate the qualitative aspects of the notional systems.

2.1 Quantitative Analysis

This study used the *RACER* system as the parametric analysis tool for conducting both the sensitivity and quantitative analyses. *RACER* has been patented by the U.S. Air Force (USAF) and has been approved by Congress for military construction Budget Estimate Submittals (BES). Before discussing the specific use of the *RACER* system, some background on the USAF's decision to use a parametric analysis tool is worth noting.

During the 1987 session of the 100th U.S. Congress, the USAF presented to the Appropriations Committee a parametric cost estimating system that could be used to prepare BESs for military construction projects. As a result, the Committee adopted Joint Resolution 395 on December 21, 1987, which states:

> The Air Force has developed a parametric cost modeling system that has the potential for providing cost estimates as an alternative to developing cost estimates based on 35 percent design status. The Conferees have no objection to the Air Force including five projects in the FY89 budget based on parametric modeling.

Subsequently, the Air Force presented a comparison of estimates prepared using the traditional 35 percent estimating process and the estimates developed using parametric modeling to the 101st U.S. Congress in 1989. The parametric estimates were found to be as accurate as traditional estimates. As a result, the Appropriations Committee adopted Congress Report 101-331, November 7, 1989, which states:

> In light of the maturing capability of parametric facility planning, the conferees have no objection to the use of parametric facilities planning for the basis of budget requests for military construction projects.

The Conferees also requested a comparative analysis of the two estimating methodologies no later than March 1, 1993. Overall, the study concluded that "...the budget estimates based on parametric facility planning were judged more accurate." The study concluded that the parametric method is equal to, or better than, the traditional method in estimating construction costs during the planning, programming, and budgeting phases of facility acquisition.

By using a parametric estimating approach, *RACER* quickly generates budget-level cost estimates, enabling the comparative analysis of conventional, teleoperated, and autonomous ordnance location and recovery systems. To better understand the application of this analysis tool, a general discussion of the parametric method and its use in *RACER* follows. Specific use of the applicable *RACER* models is explained in section 2.1.2.

2.1.1 Parametric Modeling using *RACER*

Parametric cost estimating is a process that quickly generates budget-level cost estimates with minimal input information. Parametric estimating implies that the cost estimate uses a top-down approach.

In *RACER*, equations, or algorithms, are programmed into the system to calculate the necessary quantities of equipment, material, and labor after the user provides the minimum necessary site information. This minimum necessary site information is often referred to as the required parameters. Selection of these required parameters generates default values for a number of secondary parameters that further define the type and amount of effort needed to remediate the site. *RACER* generates a reasonable cost estimate using only required parameters; however, if the user has more detailed information, the secondary parameter values may be modified to create a more precise, site-specific estimate.

The *RACER* parametric analysis tool used in this study employs remediation technology cost models to create generic engineering solutions for environmental projects, technologies, and processes. These cost models use knowledge bases derived from environmental science and engineering principles, and, where available, historical project information, government laboratories, construction management agencies, vendors, contractors, and previous engineering analyses. This approach makes the *RACER* model unique in that new engineering technologies may be added to the system, based on engineering principles. No historical data are required. Therefore, the cost/benefit of new technologies, such as robotics, may be compared on the same basis with traditional approaches.

2.1.2 Using the *RACER* System

The following sections describe the remediation technology cost models in *RACER* that were used in this study.

Ordnance and Explosive Waste Remediation Model

This model provides the cost of locating, marking, and removing ordnance from munitions-contaminated sites. This model does not include the cost of remediating soils contaminated with chemicals and by-products of exploded or ruptured ordnance, such as primers, propellants, and chemical warfare agents. Estimating the cost of remediating these hazardous substances would be performed with another model such as Incineration (On-Site) or In-Situ Biodegradation (Land Treatment). The Ordnance and Explosive Waste Remediation model will estimate the cost of providing air monitoring if chemical warfare agents are suspected.

The required parameters for this model include site size (acreage), depth of the search, range type, and ordnance density. Secondary parameters address such issues as the number of Explosive Ordnance Disposal (EOD) technicians, and the type of magnetometer and ordnance-locating method to be used. In this model, the ordnance is located and recovered by two-man teams of EOD technicians. The teams and overall site operations are managed by master EOD technicians.

Excavation, Buried Waste Model

Although the Ordnance and Explosive Waste Remediation model includes the cost of heavy equipment such as a tractor with a plow blade or a backhoe, it may at times be necessary to remove considerable amounts of overburden to expose the ordnance, or the soil itself may be contaminated with hazardous substances. For these conditions, the Excavation, Buried Waste model can be used to estimate the costs associated with excavating and backfilling a contaminated site. This is especially important when safety regulations dictate that shoring, such as sheet piling or side slope, be used to prevent a cave-in during excavation.

The required parameters for this model include the volume of the excavation, side wall protection, and the type of excavation equipment. Secondary parameters address such concerns as the amount of hand excavation that will be required around buried drums and the amount of off-site borrow material that will be required. This model allows the estimator to fine-tune the excavation costs by modifying specific equipment-operating parameters, such as the percentage of the excavator bucket that is filled with material.

Clear and Grub Model

Although the Ordnance and Explosive Waste Remediation model includes assemblies for estimating the cost of removing vegetation, the Clear and Grub model can be used to estimate the costs of removing vegetation and debris from the soil. The first component of this model, clearing, estimates the costs of removing vegetation, such as trees, shrubs, and brush. The second component of this model, grubbing, estimates the costs of removing roots and debris so that the underlying soil is exposed.

The required parameters for this model include the acreage and the percentage of moisture in the soil. Secondary parameters include such items as the number of tree stumps per acre and the extent to which the soil volume increases (swells) upon removal. This model also permits the user to estimate the cost of loading, hauling, and disposing of the debris at an off-site location.

Safety Level

Safety levels are used to define the safety requirements for various levels of environmental hazards. These designations are based on Occupational Safety and Health Administration (OSHA) regulations in 29 CFR Part 1910. Safety Level E represents a no hazard condition, and Safety Level A represents the most hazardous environmental conditions. Because people and equipment working under hazardous environmental conditions are generally less productive, *RACER* uses safety levels to account for the reduction in labor and equipment productivity.

Safety Level E has no impact on labor or equipment. On the other hand, Safety Level A requires that personnel wear a fully encapsulating suit with self-contained breathing apparatus. As a result of these requirements, the physical movements of the operator and the equipment in a Safety Level A situation are impacted, and this diminishes the amount of work that can be produced in a given time frame. With Safety Level A, labor productivity is reduced to 37 percent of normal (Safety Level E) productivity, and equipment productivity is reduced to 50 percent of normal productivity. *RACER* does not adjust the productivity for material cost components across safety levels. The safety levels and their productivity output compared to normal conditions are provided in the table below.

Safety Level	Material Productivity	Labor Productivity	Equipment Productivity
A	100%	37%	50%
B	100%	48%	60%
C	100%	55%	75%
D	100%	82%	100%
E	100%	100%	100%

An analogy may be drawn between the safety level and the degree of care that must be taken when remediating ordnance. The *RACER* system defaults the safety level of all Remedial Action models to Safety Level D, including the Ordnance and Explosive Waste Remediation model. If Safety Level D is inappropriate for the site conditions, then the user must select another safety level. For instance, Safety Level A or B may be recommended for the Ordnance and Explosive Waste Remediation model if chemical warfare agents are suspected. Finally, RACER allows the user to modify the estimate for the actual hazardous conditions by including the secondary parameter Air Monitoring in the Ordnance and Explosive Waste Remediation model. This parameter adds in air monitoring costs if chemical warfare agents are suspected.

Project Duration

The aforementioned Site Cost models provide direct costs. In order to determine "loaded" or project costs, the Contractor models that estimate General Conditions and Overhead and Profit are run to complete the *RACER* estimating process. However, before the Contractor Models can be run, the user must first determine the project schedule so that appropriate cost escalation can be made to the midpoint of the project.

The Ordnance and Explosive Waste Remediation model includes as a default a secondary parameter called Project Duration. Project Duration breaks out the remediation time period into the days of site setup and the weeks of operation required. The Ordnance and Explosive Waste Remediation model defaults the value of this parameter to normal conditions, or Safety Level E. This parameter is influenced by such factors as the site size and the ordnance density, but it is not affected by the safety level. However, the costs are adjusted to account for increasing safety level. In order to determine the adjusted project duration for a given safety level, the project duration is divided by a weighted productivity factor. The weighted productivity factor is determined by comparing the field time required to excavate an amount of buried waste at varying safety levels. By dividing the normal project duration by the weighted productivity factor for a given safety level, the user will then have an approximation of the project duration at any safety level, in addition to Safety Level E. The productivity factors are given in the table below.

Safety Level	Project Duration Productivity Factor
A	45%
B	55%
C	68%
D	95%
E	100%

The adjusted project duration is then used in the General Conditions model to determine the costs of providing project costs, such as an office trailer, storage locker, portable toilet, warning signs, etc. at the remediation site. The project duration can also be used to assess the probable timeline to complete the remediation process. This is especially important when considering teleoperated or autonomous systems, since these systems may not perform at the same rate as conventional ordnance crews.

2.2 Qualitative Analysis

Many decision support systems are based on quantitative techniques that require numerical data. However, in many complex, real-world, decision-making situations such as this, the available information is not numerical. Rather, this information can be expressed as words or phrases in a natural language. These words or phrases are termed linguistic variables and can be provided by practitioners in a given field. The notional analysis methodology offers a means to evaluate more subjective, or less quantifiable, aspects of autonomous or teleoperated systems.

This qualitative analysis may be best illustrated by using the history of automobile manufacturing technology and processes as an example. In the early 1920s, many of the tasks involved in assembling an automobile were performed by hand. Although at the time this was the most effective method of producing a car, there were adverse impacts on the workers' health and welfare, such as fatigue, that led to unsafe workplaces by modern standards. As automotive manufacturing technology progressed, tools and machinery were developed to manufacture cars using less human labor in repetitive tasks or under hazardous conditions. Now, in modern automotive assembly plants, the majority of manual operations on assembly lines have been replaced with robotic components. This has allowed automobile manufacturers to remain competitive in a global economy. However, a secondary, less quantifiable, benefit has been the overall improvement in worker health and safety. Notional analysis lends itself well to realizing these types of implicit benefits by helping to identify, through the sensitivity analyses, the potential areas of resultant benefits, such as improved worker health and safety. The effects of these areas on performance can then be observed and tracked. Finally, the impact levels of each potential area of resultant benefit can be determined.

The objective of this section is to present a decision support system, based on Fuzzy Logic, for evaluating four operating systems for performing environmental remediation for the Air Force: EOD-based line teams, man-operated machines, telerobotics, and automated machines.

2.2.1 Why Fuzzy Logic?

The evaluation of operating systems such as robotics, telerobotics, and conventional man-operated machines is very complex. This is mainly because mission requirements of the Air Force differ from requirements normally encountered in the private sector. For example, "increased personnel safety" might be considered as a very important factor for the development of telerobotics and robots for the Air Force. However, for commercial use by the private sector, other factors like profitability might be considered more important. Therefore, conventional economic analyses used for commercial investments, such as "rate of return" or "payback period" are not applicable in this study since information about "safety" or other related factors is not numerically available. Most of the information can be obtained based on past experiences of military personnel. This type of expert information is generally "linguistic" in nature rather than numerical. For example, an expert's view on the safety of telerobotics might be expressed in linguistics by saying, "using the automated machines will highly increase personnel safety," or "using a man-operated machine lowers the personnel safety." This type of linguistic information is very important and must be included in the evaluation of the conventional, telerobotic, and autonomous systems.

Analysis of Air Force mission requirements indicates that most of the factors that determine the applicability of robotic equipment are not numerical. They are linguistic in nature and can only be obtained from experts and Air Force personnel. Considering the complexity of this issue, various decision support systems used for evaluating robotics and telerobotics were investigated, such as:

- rate of return on investment analysis
- net present value analysis
- pay back period analysis
- utility theory
- neural network
- knowledge-based expert systems
- probability analysis.

Although these classical models are useful, their applicability is limited in situations that require subjective, linguistic analysis. Inherent to each of these methodologies is a numerical-based measurement system that assesses the alternatives. Thus, none of the above models provides the framework to assess the interrelated benefits of robotic systems, which are often not quantifiable by traditional evaluation methods.

New methods in Fuzzy Logic allow information to be elicited heuristically and analyzed based on linguistics rather than traditional numerical systems. Therefore, Fuzzy Logic was implemented for developing a decision support system for evaluating robotic and telerobotic systems performing environmental remediation and other missions.

2.2.2 Qualitative Analyses using Fuzzy Logic

Fuzzy Logic is based on fuzzy set theory, which is a generalization of ordinary set theory. It provides a conceptual framework as well as a mathematical tool to solve problems which are often obscure. Fuzzy Logic is used where the quantitative and detailed information to evaluate uncertainty is not available. When this information can only be expressed in qualitative or linguistic terms, it is labeled fuzzy information. Uncertainty factors such as "bad weather," "poor design," or "weak management" are examples of fuzzy information. A linguistic variable in fuzzy logic is a variable whose values are not numbers but are words or phrases in a natural or synthetic language. The practical application of fuzzy set theory in decision analysis is very complex. The mathematical calculations are shown at the end of this section.

Considering the complex characteristics of the factors that impact Air Force missions, it was determined that Fuzzy Logic, based on linguistic analysis, provides the most suitable approach for evaluating various operating systems. The Fuzzy Logic implemented in this model captures most of the information needed to accurately evaluate the conventional and automated systems. The model allows heuristic factors to be included in the evaluation. The following steps were taken in the development of the model.

Step One:

Step one in developing the proposed model for evaluation was to identify major factors that impact the Air Force mission. These factors are listed in the first column of the following tables. This column includes: 1) socio-economic and technology factors, and 2) operational factors. Although this may not be a comprehensive list, most of the major factors are included. The model is flexible and allows other factors to be added later as they are identified.

Step Two:

In step two, a weight factor was assigned to each factor as illustrated in the second column of the table. These weight factors show the importance of each issue to the Air Force in the context of utilizing various operating systems, such as "Man-operated Machine" or "Telerobotics." For example, the weight factor for "Increased Personnel Safety" was considered as very high (H+). This indicates that safety is a very important factor in evaluating Air Force operating systems. These weight factors are based on the opinion of this project's investigators, and the values could be changed in the model to analyze various experts' views and opinions. It is proposed that in the future, a survey of various experts in the military be conducted in order to estimate more accurate weight factors.

Fuzzy Logic for Decision Support System in Evaluating Robotic and Telerobotic Systems to Perform Environmental Remediation (Impacts on the goal)

Factors impacting on goal of a mission for various operating systems	Weight Factor (w)	Operation Systems			
		EOD Base Line Team	Man-operated Machine	Tele-robotics Machine	Autonomous Machine
Socioeconomic and Technology Factors					
Increasing personnel safety	H+	L-	L	H	H+
Improving productivity (see note 1)	M	L-	H	H	M
Increasing comfort of the working environment	L	L-	L	H	H+
Reduces number of personnel needed for operation	H+	L	L	H	H+
Increases performance reliability (see note 2)	M+	H	M	H+	H
Increases the Air Force's technological capability in automation and robotics	M+	L-	L-	H	H+
To contribute to the Joint Robotics Program established by the DOD	H+	L	L-	H	H+
Reduce environmental impacts	H	L-	L-	H+	H+
Improves thoroughness and mission accomplishment (see note 3)	H+	H	H	H+	H+
Increases consistency and accurate characterization	M	H+	M	H	H-
Leverage manpower and assets	H	L-	L	H	H
Reduce overall range clearance time	M	L-	M	H	H
Increases the dual use applications that transfer Wright Lab's automation technologies to other governmental agencies and to private industry	M	L-	L-	H+	H+
Current level of knowledge about the system (see note 4)	L	H+	H	L	L
Degree of interest in the Air Force to develop the system	L	L	L	H	H
Ease of technological issues associated with the system	M	H	M	L	L
Degree of confidence in the life expectancy of the system (see note 5)	L	H	H	L	L-
Degree of human expertise needed to do the work (see note 6)	L	H	H	M	L-

Fuzzy Logic for Decision Support System (cont.)

Factors impacting on goal of a mission for various operating systems	Weight Factor (w)	Operation Systems			
		EOD Base Line Team	Man-operated Machine	Tele-robotics Machine	Autonomous Machine
Operational Factors					
Capability of the system to work on bad topography	L	H+	H	L	L-
Capability of the system to work at inaccessible locations	M	H+	H	M	M
Effectiveness of the system to work on the large size sites	L-	L-	L	H	H
Capability of the system to work in bad weather	L	L	M	H	H+
Capability of the system to work in dark	L	L	L	M	H+
Capability of the system to work 24 hours continuously	L	L	L	M	H+
Capability of the system to maneuver quickly	L	H+	H	M	M
Degree of overhead insurance reduction	L	L-	L	H	H
Total Evaluation for each Operating System Based on Weight Factors	100%	M-	M	H	H+

Key:

H: High M: Medium L: Low +: Above -: Below

NOTES: Clarification for factor definitions.

1. Productivity is defined as cubic yards of dirt moved per hour by the different options. This definition does not account for multiple shifts or multiple pieces of equipment. The higher scores are based on the premise that a skilled excavator operator can achieve the same or higher levels of productivity than an autonomous excavator with sensor systems.

2. Performance reliability is the likelihood that that the option will accomplish the work/mission assigned. This definition does not include the mechanical reliability of the machines. The moderate score on the man-operated machine is based on an excavator without the supporting sensor suite found on the robotic systems. The telerobot is scored slightly higher because of operator's decisions may improve overall reliability.

3. Thoroughness and mission accomplishment includes combat effectiveness for combat missions.

4. Current level of knowledge about the system scores lower against newer technologies because of the unfamiliarity and lack of training when bringing any new technology to practicality.

5. Degree of confidence in the life expectancy of the system takes into account the rapid advance of technologies. That is, the robot technology will advance rapidly making the life expectancy short for any robotic option.

6. Degree of human expertise and training needed to maintain preficiency and safety will be higher in the manned systems.

Step Three:

In this step, for each of the four operating systems (EOD team, man-operated machine, telerobotics, and automated machine), the impacts of various factors (e.g., safety, productivity, etc.) were estimated. The results are shown in the last four columns of the table. For example, the "automated machine" is expected to highly (H+) "increase personnel safety." These linguistic values reflect the investigators' view, and they can be changed and modified by other experts to evaluate the operating systems.

Step Four:

In this step, the linguistic weight factors were multiplied by the linguistic factors for each operating system and the results were added based on fuzzy set theory. The result is the total value for each operating system, as shown in the last line of the table.

The results of fuzzy calculation show that the Automated Machine is ranked as very high (H+), the telerobotic machine is ranked as high (H), the man-operated machine is ranked medium (M), and the EOD baseline team is ranked as low-medium (M-).

Using this model, the Air Force can investigate the impact of changes in various operating systems as well as the level of importance (weight factor) for each issue. The model can be used as a basis for group discussion and decision making as well as sensitivity analyses for various factors. The model can justify the Air Force's strategic plan for the development of automation and robotics in the future. The model is flexible and easy to use because it is based on words and linguistics. It is recommended that in the future, the model be computerized so that the methodology can be implemented by various personnel in the Air Force.

2.2.3 Mathematics Supporting the Fuzzy Logic

Fuzzy set analysis allows a linguistic approach to the evaluation of alternatives based on natural language expressions by linguistic variables. A linguistic variable is a variable whose values are not numbers but words or phrases in a natural or synoptic language. Thus, each word "x" in a natural language can be viewed as a summarized description of a fuzzy set A(x) of a universe of discourse "U" in which A(x) represents the meaning of x. Linguistic variables and fuzzy sets have the relationship of goal and tool. Manipulation of linguistic variables is the goal, and fuzzy set theory is a tool to achieve that goal. Fuzzy sets can be expressed mathematically as follows:

$$A = [x|\mu_A(x)]$$

where A = fuzzy set; $\mu_A(x)$ = membership value between zero and one; and x = a scale element between zero and ten. Our proposed linguistic approach uses the extension principle. The extension principle results in the following definitions of fuzzy addition, multiplication, and division. If A and B are two fuzzy sets as follows:

$A = [x|\mu_A(x)]$
$B = [y|\mu_B(y)]$

in which x and y = elements of universe X, and universe Y, respectively; then the addition, multiplication, and division can be done by the following fuzzy mathematics:

$A \oplus B = [(x + y)|\min(\mu_A(x), \mu_B(y))]$
$A \otimes B = [(x \bullet y)|\min(\mu_A(x), \mu_B(y))]$
$A \varnothing B = [(x \div y)|\min(\mu_A(x), \mu_B(y))]$

in which $\oplus$, $\otimes$, and $\varnothing$ are fuzzy arithmetic operations of addition, multiplication, and division of two fuzzy sets; and +, $\bullet$, and $\div$ are the normal arithmetic operations. When the result of the calculation leads to more than one membership value for a given scale, the highest membership value is selected.

Now, using the fuzzy set mathematics described in the above section, it is possible to evaluate the total value for each operating system by multiplying the weight factors times the values, and then adding them up by using the following fuzzy set equation:

$[R] = \sum [W_i] \otimes [R_i] \varnothing \sum [W_i] \quad i = 1 \text{ to } n$

in which [R] = a fuzzy set which represents the fuzzy value of the total evaluation of an operating system; n = total number of factors; $[W_i]$ = fuzzy weight factor of the issue "i," and $[R_i]$ = fuzzy value of factor "i." This equation uses Zadeh's extension principle for extending functions over the integers to functions over fuzzy subsets based over the integers.

However, there are some difficulties in applying this technique. One problem is how to assign the membership values of a fuzzy set to represent a linguistic variable. Since this is the starting point for any fuzzy set analysis, it is obviously important for the membership values to be as realistic as possible. One way to solve this problem is to conduct a sensitivity analysis on selected fuzzy sets to determine the impact of varying the membership values. For further explanation and details of mathematical theory approach, see the IEEE paper by Dr. Kangari in Appendix 3. Another source of reference is the paper by L.A. Zadeh, "Outline of new approach to the analysis of complex systems and decision processes," IEEE Trans. Syst., Man, Cybern., vol. SMC-3, no. 1, pp. 28-44, Jan. 1973.

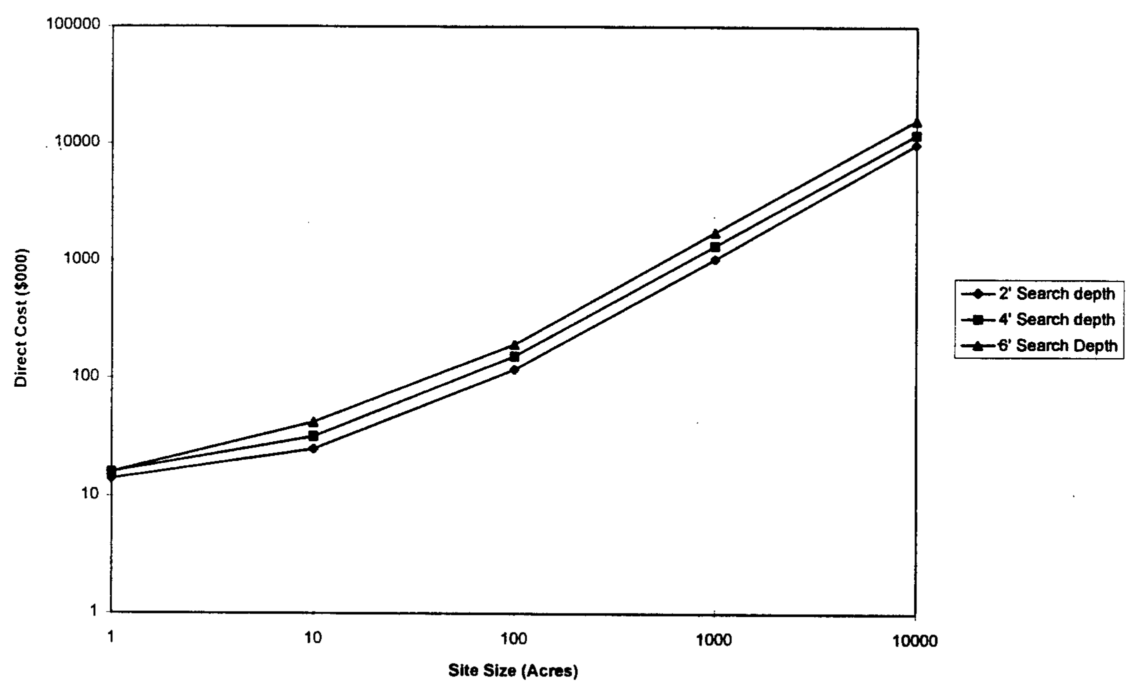
3.0 Results

3.1 Performance-Based Analysis

Parametric cost modeling enables one to easily observe the way in which varying site parameters (e.g., site size, ordnance search depth, terrain type, ordnance density, etc.) impact the total remediation cost. Through parametric estimating, it is possible to estimate costs for multiple site scenarios, each scenario containing a unique combination of site parameters, and compare costs for the conventional, teleoperated and autonomous processes in each scenario.

Before the performance of these systems can be assessed, it is necessary to identify all of the parameters pertaining to the site and understand the impact each parameter has on the project. In other words, it is necessary to analyze the sensitivity of the cost and duration to variations in site parameters, and to understand which parameters have the greatest impact on cost and duration. To gain an understanding of these effects, several parametric estimates were created using the *RACER* Ordnance and Explosive Waste Remediation Model, and the effects of varying the parameters were observed. The results of these analyses are shown in the plots and tables below. The first analysis considers the relationship of cost to site size for three different ordnance search depths. This analysis assumes that the terrain type does not change.

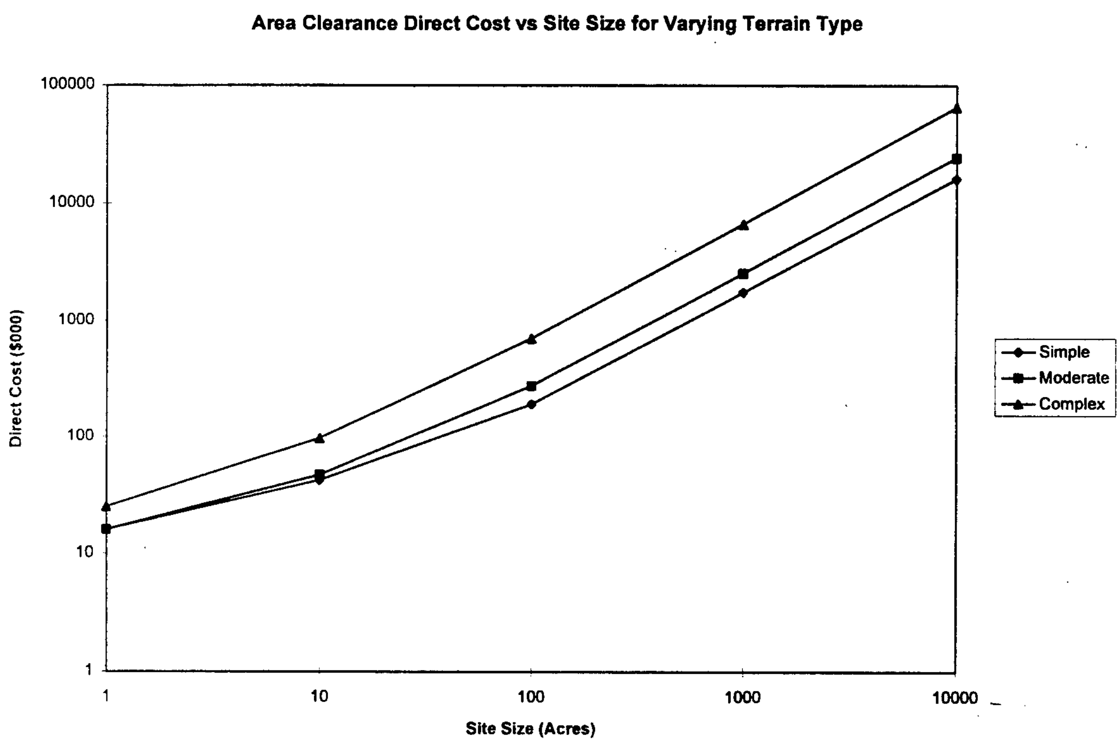
Area Clearance Direct Cost vs Site Size for Varying Search Depths



The data used to plot this graph are shown in the table below.

Project Direct Costs ($000) vs Site Size for Varying Search Depth					
	Site Size (Acres)				
Search Depth (ft)	1	10	100	1,000	10,000
2	14	25	117	1,032	9,935
4	16	32	152	1,340	12,071
6	16	42	191	1,749	15,973

The second analysis considers the effect of varying the terrain type for a constant search depth of 8 feet.



The data used to plot this graph are shown in the table below. In this table, the simple terrain type refers to flat terrain with barren or low grass; moderate refers to rolling terrain with barren or low grass; and complex terrain refers to hills or large rocks with heavy shrubs and trees.

Project Direct Costs ($000) vs Site Size for Varying Terrain Types					
	Site Size (Acres)				
Terrain Type	**1**	**10**	**100**	**1,000**	**10,000**
Simple	15	42	191	1,749	15,973
Moderate	16	47	276	2,542	24,258
Complex	25	97	705	6,661	65,239

As shown by the above plots, the single biggest cost driver for area clearance is the site size. Secondarily, as the site size increases, the cost becomes more heavily influenced by terrain type. For example, on a ten-acre site with a search depth of 8 feet, changing the terrain type from "flat - barren or low grass" (simple) to "hills/large rocks w/ heavy shrubs and trees" (complex) results in a 130% increase in cost. For a 10,000-acre site, changing the terrain type from simple to complex results in a more than 300% increase in cost. Within the range of search depths considered in this study, doubling the search depth results in an average cost increase of approximately 30%.

Once the impacts of the various site parameters are understood, it is necessary to establish a set of uniform assumptions regarding the physical characteristics of the sites and the productivity of the conventional, telerobotic, and autonomous systems. In addition, it is necessary to focus the parametric estimates only on those steps of the remediation process in which the subject equipment is employed.

To evaluate the costs and benefits of telerobotic and autonomous equipment, a series of scenarios was developed, and separate parametric estimates for conventional, telerobotic, and autonomous equipment were produced for each scenario. The scenarios were created to evaluate the systems under varying site conditions. Therefore, a unique set of site parameters was associated with each scenario. The scenarios were subjectively ranked in order of increasing site complexity. The site complexity rating encompassed site parameters such as site size, ordnance search depth, ordnance density, and terrain type. These parameters are required inputs in the parametric models. That is, values for these parameters must be supplied in order to produce estimates.

The parametric models used to produce the estimates contain performance and productivity data for conventional excavation equipment. However, such data are not available for the telerobotic and autonomous equipment. Therefore, it was necessary to make assumptions regarding the productivity and performance characteristics for this equipment. It was also necessary to make assumptions regarding staffing (labor) requirements for the telerobotic and autonomous systems.

In creating parametric estimates, it is possible to tailor the assumptions to produce the desired output. Such was not the case in this study. Assumptions regarding site characteristics, machine productivity, and staffing requirements were carefully chosen to facilitate unbiased evaluation of the conventional, telerobotic, and autonomous equipment. All estimating assumptions are discussed in detail in the following sections of this report.

3.2 Mission and Scenario Definition

Missions are based on DoD requirements and are therefore fixed. Based on the results of sensitivity analyses, a range for the scenarios for these missions was established to bound site conditions. This section addresses specific quantitative results for multiple missions and scenarios. Analogies and assumptions were made in order to quantify the performance of the telerobotic and autonomous systems. This information was incorporated in the parametric modeling tool to yield the following results.

The following three missions types were analyzed in this study: hazardous waste removal, area clearance, and unexploded ordnance (UXO) removal. This section describes the scenarios and assumptions used to produce parametric cost estimates for each mission. Scenarios are classified by complexity and represent the relationship between the variables analyzed in the sensitivity analyses.

3.2.1 Hazardous Waste Removal Mission

The mission of hazardous waste removal is limited to a treatment train that includes the removal of a known amount of contaminated soil from a site. Unit operations for this treatment train include mobilization to the site, excavation, and staging the excavated soil for further processing. Treatment, transportation, and disposal of the contaminated soil are not included in the mission's treatment train.

3.2.1.1 Hazardous Waste Removal Mission Scenarios

Listed below are five scenarios pertaining to excavation of hazardous waste. The scenarios are listed in order of increasing complexity. The primary factor in determining complexity is the volume of contaminated soil. Other factors that influence complexity include the presence of buried drums and the requirement for excavating in lifts rather than excavating continuously. When buried drums are present, it is assumed that excavation will be performed in six-inch lifts and that the last three feet of soil around the drums will be hand excavated. These assumptions are based on defaults residing in the *RACER* model.

Low Complexity

The low complexity scenario is modeled after a Petroleum, Oils, and Lubricants (POL) spill site at a typical Air Force Base Exchange (BX) Service Station. The site contains approximately 3,000 total bank cubic yards of soil. This site contains no buried drums or other obstructions; therefore, continuous excavation is possible. The excavation dimensions are 100' x 100' x 5' deep, and sidewall protection is assumed to be unnecessary.

Moderately Low Complexity

The moderately low complexity scenario is modeled after a drum disposal pit containing approximately 5,600 total bank cubic yards. The pit contains 75 buried drums containing PCBs. Most of the drums are assumed to be leaking. The location of the drums necessitates that excavation be performed in six-inch lifts. Also, the last three feet of soil around the drums must be hand excavated. The excavation size is approximately 150' x 150' x 6' deep, with a 1:1.5 side slope being used to prevent cave-in of the side walls.

Moderate Complexity

The moderate complexity scenario is modeled after a base landfill which is known to contain mostly household wastes. The approximate soil volume is 50,700 total bank cubic yards. The site contains no buried drums, and continuous excavation is possible. The excavation size is approximately 360' x 360' x 10' deep, with a 1:1.5 side slope being used to prevent cave-in of the side walls.

Moderately High Complexity

The moderately high complexity scenario is based on a firing range containing approximately 236,700 total bank cubic yards of lead-contaminated soil. Contamination in the soil extends two feet below ground surface. Soil is excavated continuously. The excavation size is approximately 2,100' x 2,100' x 2' deep. The model defaults a 5.5 CY (cubic yard) excavator bucket based on these parameters. However, since the excavation is only two feet deep, a 1.25 CY bucket is used.

High Complexity

The high complexity scenario for hazardous waste removal is based on a mixed waste landfill containing approximately 377,500 total bank cubic yards of soil. The landfill contains 1,000 drums which are assumed to be leaking. Excavation must be performed in six-inch lifts, and soil must be hand excavated within three feet of any drums. The excavation size is approximately 1,000' x 1,000' x 10' deep with a 1:1.5 side slope.

3.2.1.2 Hazardous Waste Removal Assumptions

Estimates for hazardous waste excavation were produced using the *RACER* Excavation, Buried Waste model. Soil volumes were calculated from excavation dimensions. The Excavation, Buried Waste model defaults to larger excavators as the soil volume increases. For conventional excavation, excavator sizes were defaulted based on the volume of soil, and machine hours were calculated using *RACER* default productivity factors.

The Excavation, Buried Waste model makes no assumptions regarding the most appropriate number of excavators for a job. However, the number of machine hours calculated by the model may be thought of as total machine hours. In other words, 1,000 machine hours may be interpreted as either one machine working 1,000 hours, or two machines each working 500 hours. Obviously, as the soil volume increases, it becomes more desirable to mobilize additional excavators to the site in order to reduce the overall project duration. For the conventional scenarios, the number of excavators was allowed to increase with increasing soil volume. Project durations were derived from the calculated machine hours. For Safety Level E (no hazards), *RACER*-calculated machine hours were used without modification. However, the project durations for Safety Levels D and higher were extended to account for decreased productivity resulting from increasing safety level. In all conventional estimates, the construction duration specified in the General Conditions model was increased to account for increased project duration resulting from increasing safety level.

Teleoperated and autonomous operations are based on using a CAT 325L Long Reach Hydraulic Excavator with a 3/4 cubic yard bucket. Performance data for the CAT 325L is not available in the Excavation, Buried Waste model. Therefore, it was necessary to calculate the machine hours manually. Based on information from the Caterpillar Performance Handbook, a CAT 325L cycle time of 25 seconds and a heaped bucket capacity of 1.13 loose cubic yards was assumed. The equipment cost for the CAT 325L and the calculated machine hours were inserted into the Excavation, Buried Waste model to develop costs for the teleoperated and autonomous scenarios. The teleoperated and autonomous equipment are assumed to be one of a kind. Therefore, unlike the conventional excavation scenarios, all teleoperated and autonomous excavation estimates are based on a single excavator, regardless of the size of the site.

An eight-hour work day was assumed for the conventional and teleoperated operations. For the autonomous operation, a 24-hour work day was assumed, with a 20% down-time allowance to allow for refueling and minor maintenance, giving 19.2 hours per day for excavation activities. However, since the excavator is continuously moving soil in the hazardous waste removal scenarios, the increased down-time allowance was deemed appropriate. In all scenarios, a five-day work week was assumed. All scenarios were assumed to require one-half full time equivalent (FTE) of a site superintendent and one FTE for a site project manager. These personnel are assumed to be non-local and therefore require travel expenses and per diem. For the conventional and teleoperated scenarios, one operator and one maintenance person were assumed for each excavator. For the autonomous scenarios, one maintenance person was assumed. Operators and maintenance personnel were assumed to be local. The excavation equipment was assumed to be rented unless otherwise noted. Support equipment includes rental of one automobile for the entire project duration. Projects of less than one month in duration were assumed to require no office trailers or toilets. Projects exceeding one month in duration were assumed to require one office trailer and one toilet for the entire project duration.

3.2.1.3 Hazardous Waste Removal Results

Table 1 below presents the total machine hours, number of excavators, and total project durations for each of the five hazardous waste removal scenarios. For each of the scenarios, nine estimates were prepared. Five of these estimates represented model runs for conventional remediation at safety levels A, B, C, D, and E. The remaining four runs were for the rental and purchase options for the telerobotic and autonomous systems. Table 1 shows a sampling of the run estimates; however, Figure 1 represents all the sample runs for each scenario.

Scenarios in which multiple excavators are used for conventional excavation are indicated in bold and italics type. In the duration tables below, the symbols CONV-E and CONV-A refer to a conventional excavator working at Safety Levels E and A, respectively. These safety levels bound productivity. The symbol TELE refers to a teleoperated excavator, and AUTO refers to a totally autonomous excavator. Safety level was assumed to have no impact on teleoperated and autonomous operations. This is based on the assumption that the operator is completely removed from the hazardous environment.

RACER Results for Low Complexity Scenario				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Machine Hours	12	28	17	17
No. of Excavators	1	1	1	1
Hours per Day	8	8	8	19
Work Days	2	4	3	1
***RACER* Results for Moderately Low Complexity Scenario**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Machine Hours	49	106	91	91
No. of Excavators	1	1	1	1
Hours per Day	8	8	8	19
Work Days	7	14	12	5
***RACER* Results for Moderate Complexity Scenario**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Machine Hours	190	395	462	462
No. of Excavators	*2*	*2*	1	1
Hours per Day	8	8	8	19
Work Days	12	25	58	25
***RACER* Results for Moderately High Complexity Scenario**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Machine Hours	2,097	4,745	2,887	2,887
No. of Excavators	*4*	*4*	1	1
Hours per Day	8	8	8	19
Work Days	66	149	360	150
***RACER* Results for High Complexity Scenario**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Machine Hours	3,867	8,023	9,407	9,407
No. of Excavators	*4*	*4*	1	1
Hours per Day	8	8	8	19
Work Days	121	251	1,175	490

Table 1: Hazardous Waste Remediation Duration Results

The data contained in Table 1 were used to generate total project costs for the hazardous waste remediation. These total project costs are plotted in Figure 1. The specific cost data is contained in Table 2.

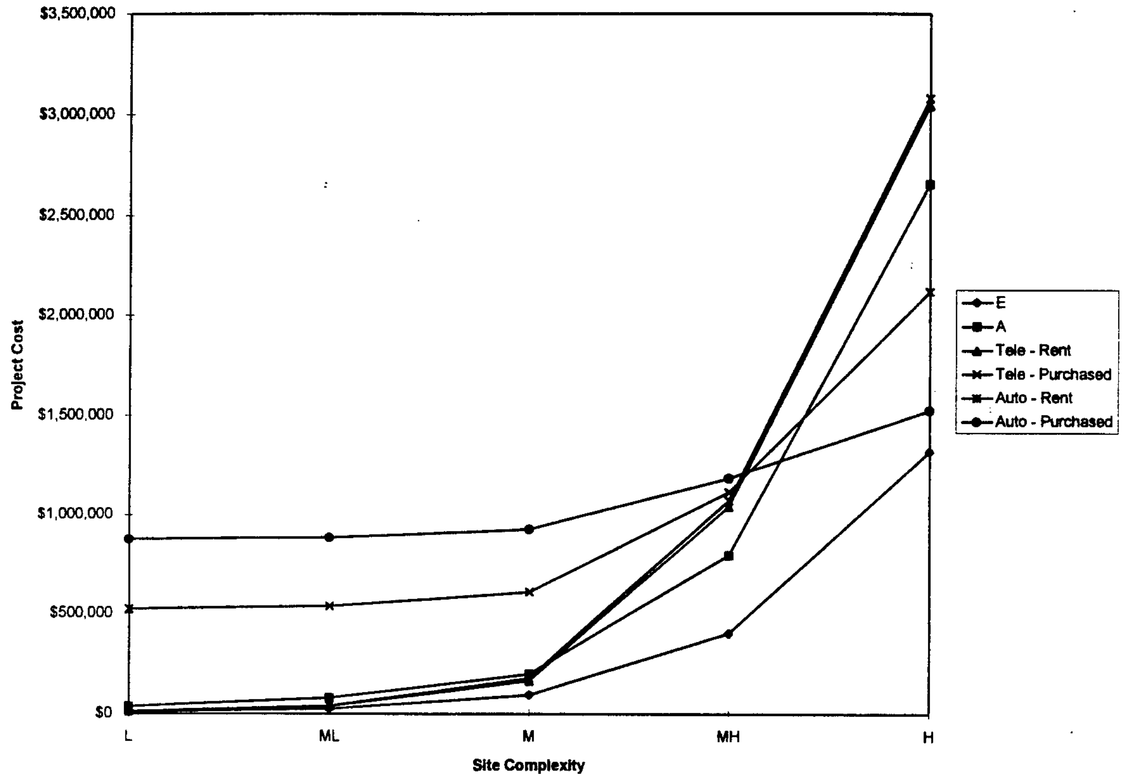


Figure 1: Multi-system Hazardous Waste Excavation

Total *RACER* Project Costs ($000) by Site Complexity					
	Low	Mod Low	Mod	Mod High	High
CONV- E	9	23	92	399	1,320
CONV-A	36	78	196	796	2,656
TELE-RENT	12	36	162	1,043	3,044
TELE-PURCH	523	535	607	1,117	2,120
AUTO-RENT	12	38	175	1,073	3,079
AUTO-PURCH	877	885	927	1,187	1,525

Table 2: Hazardous Waste Excavation Total Restoration Costs

In Figure 1, for the Low, Moderately Low and Moderate site complexity scenarios, the elimination of personal protective equipment (PPE) requirements for the teleoperated and autonomous processes render the teleoperated and autonomous more desirable than conventional excavation in PPE. However, in the Moderately High site complexity scenario, the increase in project duration required for the teleoperated and autonomous equipment tends to offset any cost savings realized from the elimination of PPE requirements. For the High site complexity scenario, the durations become long enough to render purchase of either the teleoperated or autonomous equipment more desirable than using conventional equipment with full Safety Level A PPE.

In the two most severe site complexity scenarios, allowing the number of conventional excavators to increase tends to bias the results in favor of conventional equipment. In order to compare teleoperated and autonomous equipment with conventional excavation equipment, a second set of estimates was developed in which a single CAT 325L excavator with a 3/4 cubic yard bucket was employed for the conventional, teleoperated, and autonomous operations in all five scenarios. The results of these estimates are shown in Table 3, below.

RACER Results for Low Complexity Scenario				
	CONV-E	CONV-A	TELE	AUTO
Machine Hours	17	37	17	17
No. of Excavators	1	1	1	1
Hours per Day	8	8	8	19
Work Days	3	5	3	1
RACER Results for Moderately Low Complexity Scenario				
	CONV-E	CONV-A	TELE	AUTO
Machine Hours	91	196	91	91
No. of Excavators	1	1	1	1
Hours per Day	8	8	8	19
Work Days	12	25	12	5
RACER Results for Moderate Complexity Scenario				
	CONV-E	CONV-A	TELE	AUTO
Machine Hours	462	994	462	462
No. of Excavators	1	1	1	1
Hours per Day	8	8	8	19
Work Days	58	118	58	25
RACER Results for Moderately High Complexity Scenario				
	CONV-E	CONV-A	TELE	AUTO
Machine Hours	2,887	6,209	2,887	2,887
No. of Excavators	1	1	1	1
Hours per Day	8	8	8	19
Work Days	360	777	360	150
RACER Results for High Complexity Scenario				
	CONV-E	CONV-A	TELE	AUTO
Machine Hours	9,407	20,231	9,407	9,407
No. of Excavators	1	1	1	1
Hours per Day	8	8	8	19
Work Days	1,175	2,529	1,175	490

Table 3: Constant Excavator Hazardous Waste Remediation Duration Results

Figure 2 illustrates the total project costs for the scenarios. In comparing this information to Figure 1, one can see the dramatic increase in exponential nature of the rental equipment remediation costs. (Note the vertical scales on these figures are different.)

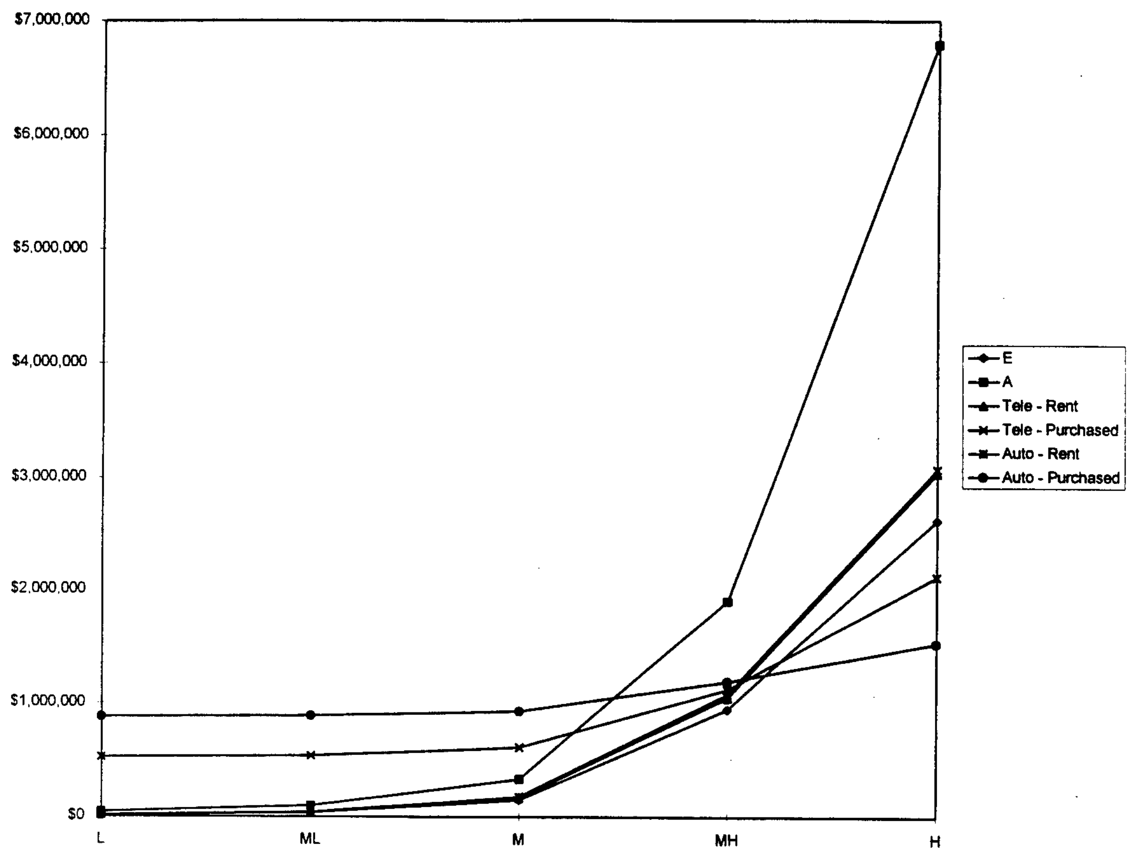


Figure 2: Multi-system Constant Excavator Hazardous Waste Excavation

The data used to produce this plot are shown in the Table 4, below.

Total *RACER* Project Costs ($000) by Site Complexity					
	Low	Mod Low	Mod	Mod High	High
CONV-E	11	34	146	943	2,621
CONV-A	42	96	330	1,902	6,789
TELE-RENT	12	36	162	1,043	3,044
TELE-PURCH	523	535	607	1,117	2,120
AUTO-RENT	12	38	175	1,073	3,079
AUTO-PURCH	877	885	927	1,187	1,525

Table 4: Constant Excavator Hazardous Waste Excavation Total Restoration Costs

Although it is unrealistic to assume that a single excavator would be used on larger sites, the results above show the relative costs of the conventional, teleoperated, and autonomous operations when the number and type of excavator is the same for all three operations. If the one-of-a-kind restriction is removed from the teleoperated and autonomous equipment, the teleoperated excavator becomes more desirable than conventional equipment with Safety Level A PPE in all rental cases. This observation holds true across all five site complexity scenarios. The economics of this function are driven by the equipment's ability to excavate material. Therefore, as the bucket size and the number of excavators increase, the conventional systems are more cost effective (refer to Figure 1).

3.2.2 Area Clearance Mission

The process of area clearance includes the search and recovery of ordnance. This mission can be broken down into multiple parts. The first is the search and recovery of any surface ordnance. Once this is completed, the area is surveyed and marked to designate areas where subsurface ordnance may exist. The search or hunting process will note the location of ordnance by Global Positioning System (GPS) and/or standard surveying techniques. After surveying, patterns are established for ordnance recovery. For the purpose of this study, the mission concludes with the ordnance being removed from the ground.

3.2.2.1 *RACER* Parameters for Area Clearance Mission Scenarios

Table 5 summarizes the required parameters used to generate *RACER* estimates for area clearance scenarios using conventional, teleoperated, and autonomous removal methods.

Required Parameter	Low	Moderately Low	Moderate	Moderately High	High	Very High
Site Size	10 acres	20 acres	75 acres	200 acres	500 acres	1,000 acres
Type of Operations	Search and Recovery	Search and Recovery	Search and Recovery	Search and Recovery	Search and Recovery	Search and Recovery
Search Depth	2 feet	1 feet	4 feet	4 feet	6 feet	8 feet
Type of Range	Demolition Area	Small Arms Range	Artillery, Long and Short Range	Bombing Range, Hard Bombs	Artillery, Long and Short Range	Bombing Range, Hard Bombs
Ordnance Density	100 items per acre	350 items per acre	50 items per acre	25 items per acre	20 items per acre	5 items per acre
Terrain	Flat, barren or low grass	Flat, low grass and few shrubs	Rolling, low grass and few shrubs	Flat, shrubs and some trees	Rolling, heavy grass and numerous shrubs	Hills or large rocks, heavy shrubs and trees
Conventional Safety Level	A, E	A, E	A, E	A, E	A, E	A, E
Teleoperated or Autonomous Safety Level	E	E	E	E	E	E

Table 5: *RACER* Parameters for Area Clearance Mission Scenarios

3.2.2.2 Conventional Area Clearance Assumptions

The conventional estimates were made using the required parameters shown in Figure 5 and taking secondary *RACER* parameters as defaults. The following assumptions were used in preparing the conventional removal estimates:

- The Ordnance and Explosive Waste Remediation model defaults a secondary parameter called "Project Duration" which breaks out the remediation time period into the days of site setup and the weeks of operation required. The Ordnance and Explosive Waste Remediation model defaults the value of this project duration parameter to normal conditions, or Safety Level E. Project duration is influenced by such factors as the site size and the ordnance density but is not adjusted by the safety level. In order to determine the adjusted project duration for Safety Level A, the project duration was divided by a weighted productivity factor. The weighted productivity factor was determined by comparing a realistic field time required to excavate an amount of buried waste at varying safety levels. This field time was determined by running the Excavation, Buried Waste model in *RACER* to determine what impact an increase in safety level (i.e., decrease in productivity) had on the rental time needed for an excavator. By dividing the normal project duration at Safety Level E by the weighted productivity factor for a given safety level, the user would then have an approximation of the project duration at each safety level. The weighted productivity factor determined using this method for Safety Level A was 0.45 compared to 1.0 at Safety Level E.

- The adjusted project duration was then used in the General Conditions model to determine the costs of providing items such as an office trailer, storage locker, portable toilet, safety signs, etc. at the remediation site for the duration of the project.

- The Contractor General Conditions model was run using defaults for all conventional applications except for the following listed below. In the Field Expenses section of the Contractor General Conditions model, the Site Project Manager, Superintendent, Clerks, Vehicles, and Survey Crew staffing requirements were set to zero. It was assumed that the tasks of a Site Project Manager, Superintendent, Clerk, and Survey Crew would be performed by EOD personnel during the site setup and search and recovery phases of the remediation. The Ordnance model defaults rental vehicles for use of the crews based on the number of personnel at the site and the duration of the project. The vehicles defaulted by the General Conditions model were therefore not needed and were set to zero.

- For Safety Level A conventional runs, the fully encapsulating level "A" safety suits were deleted from the site direct costs, since these costs were also accounted for by the Personal Protective Equipment section of the Contractor General Conditions model. The number of personnel requiring level "A" safety suits in the model was set equal to the number of Master and EOD technicians defaulted by the model.

- It is assumed that the staffing requirements predicted by the model, up to a maximum of 22 technicians, can be adequately and timely met by EOD personnel or contractors.

3.2.2.3 Teleoperated Area Clearance Assumptions

The teleoperated estimates were performed by using the direct cost assemblies from the conventional applications as a starting point. In *RACER* terminology, assemblies consist of one or more line item costs that have been grouped together to represent a complete item or task. For instance, a trench excavation assembly might include the individual line items for an excavator, operator, shoring, and any manual digging required. Next, individual direct cost assembly quantities were adjusted to reflect the assumptions that were made for these estimates. Finally, after the direct cost assembly adjustments were completed, the Contractor General Conditions and Overhead and Profit models were run to generate project costs for each site scenario. The following assumptions summarize how the teleoperated estimates were made:

- For the teleoperated application, it was assumed that the machines are one of a kind due to the system's research and development status. Therefore, in these estimates, only one machine was assumed to be available for purchase or rental. It was assumed that teleoperated equipment reduced the total number of EOD technician hours by one-half. One EOD technician was left in the direct cost assemblies to operate this equipment at a weekly rate of 40 hours per week (eight hours per day, five days per week). The number of master EOD technician hours was not reduced. Since all of the adjusted EOD technician hours were attributable to only one individual working over an extended duration, the Master EOD technician would then oversee the site on only a part-time basis. This point of view was taken since it generates the most conservative estimates.

- The assumption that only one teleoperated machine was available meant that project durations increased over the same scenarios for conventional removal for all safety levels. Inherent in this assumption is that capital equipment is limited, and remediating the site by telerobot over a period longer than by conventional means is not a problem. The estimates were also made on the basis that neither the operator or the Master EOD technician ever entered a site until it had been cleared of ordnance. By totally removing personnel from the inherent risks of ordnance remediation, all the EOD-specific safety equipment assemblies were deleted from the direct costs when using a teleoperated machine.

- One EOD technician operated the equipment for eight hours (daylight only) per day, five days per week using the assumption that direct sighting of the machine by the operator was necessary in order to operate the controls. At nighttime, this would be prohibitive because of the physical size of these sites which ranged from 10 to 1,000 acres.

- One rental vehicle, a van or pickup truck, was kept for each day that the equipment was operated based on a weekly schedule of five operating days. It was assumed that the Master technician would share the rental vehicle with the EOD technician during the time the Master technician oversaw progress at the site.

- The teleoperated equipment is equipped to locate and recover the ordnance. Therefore, these estimates do not include assemblies for manually locating and excavating the ordnance since all these functions are contained within the rental or purchase of a teleoperated system. In addition, tools and equipment used by crews to recover ordnance, such as nonsparking shovels and lifting hoists, were not necessary when teleoperated equipment was used to perform these same functions. However, costs for renting an ordnance transport truck were retained in the estimates. This truck was still needed to periodically visit the site and haul off any recovered ordnance that would be left on the periphery of the remediation area by the telerobot.

- Clearing and grubbing of the site was included in the conventional estimates. However, this activity was assumed to not be required with a teleoperated machine as the equipment is designed to search and locate in more rugged terrain and conditions than conventional crews.

- The project duration, in months, for use in the General Conditions model was determined on the basis of remediating a site at the rate of 40 operator hours per week, (i.e., eight hours per day, five days per week). Even though the total number of EOD technician hours was halved in the telerobotic estimates, the project durations were greater than some of the conventional estimate durations since only one operator was left to perform the recovery tasks of multiple teams in the more complex of the scenarios. This assumption biases the analysis against the telerobot, but is consistent with the conservative assumption throughout this study.

- The Contractor General Conditions model was run using defaults for all teleoperated applications except for the following: The value for the project duration determined in the above assumption was used for the period in which an office trailer and/or storage locker were rented. The project duration was based on an operating schedule of 40 hours per week for one machine.

- In the Field Expenses section of the Contractor General Conditions model, the Site Project Manager, Superintendent, Clerks, Vehicles, and Survey Crew manning requirements were set to zero. It was assumed that tasks of a Site Project Manager, Superintendent, Clerk, and Survey Crew would be performed by the EOD personnel during the site setup and search and recovery phases of the remediation.

Since one rental vehicle was retained in the direct cost assemblies, any additional vehicles defaulted by the General Conditions model were therefore not needed.

3.2.2.4 Autonomous Area Clearance Assumptions

The autonomous system estimates were performed by using the direct cost assemblies from the teleoperated applications as a starting point. Next, individual direct cost assembly quantities were adjusted to reflect research and development cost data and assumptions that were made for these estimates. Finally, after the direct cost assembly adjustments were completed, the Contractor General Conditions and Overhead and Profit models were run to generate project costs for each site scenario. The following assumptions summarize how the autonomous system estimates were made:

- For an autonomous application, it was assumed that the equipment is one of a kind due to the system's research and development status. Therefore, in the estimates, only one machine was available for purchase or rental. It was assumed that the number of total operating hours required by the autonomous equipment was equivalent to the number of total operating hours required by the teleoperated equipment (the hours of operation per day was not assumed to be equal). However, unlike the teleoperated estimates, it was assumed that the autonomous machines eliminated the need for EOD field technicians, and the number of Master technician hours would remain the same. All programming of the equipment would be handled by the Master EOD technician. This individual would visit the site on a part-time basis over the project duration to ensure that operations were going well and that the equipment was properly performing its search and recovery patterns.

  The assumption that only one autonomous machine was available to operate meant that project durations increased over some of the conventional removal scenarios (based on the number of conventional systems varying). However, since the autonomous machine functions independently of an operator, it was assumed that the equipment availability was at 160 hours per week (eight hours per week are allotted for equipment breakdown and minor repairs). This equates to the equipment operating autonomously for seven days per week at the rate of approximately 23 hours per day. Refueling was considered to be of short duration and could conceivably be scheduled to occur during the eight hours of downtime allotted per week.

- The estimates were also made on the basis that the Master EOD technician never entered a site until it had been cleared of ordnance. By totally removing this individual from the inherent risks of ordnance remediation, EOD-specific safety equipment was not required.

- Visual sighting of the autonomous equipment is not necessary as with teleoperated equipment since the pre-programmed equipment operates independently of an operator.

- For scenarios in which an ordnance transport truck was not defaulted by the Ordnance model (Low and Moderately Low), a rental vehicle was apportioned for the entire project duration because of the relatively short project durations. However, an ordnance transport truck was defaulted for the other four scenarios. For these longer-duration projects, a rental vehicle for the Master technician was allotted at the same number of days that the model defaulted the rental of a ordnance transport truck. Thereby, in this process, the Master technician travels to the site to oversee the off-site hauling of the recovered ordnance, for example, when a full truck load of ordnance has been recovered. Therefore, manning requirements at the site have been reduced from seven days per week to only when a truck is needed to haul off the recovered ordnance and when the Master technician checks on the overall progress being made at the site.

- The autonomous equipment is equipped to locate and recover the ordnance. Therefore, these estimates do not include assemblies for manually locating and excavating the ordnance since all these functions are contained within the rental or purchase of an autonomous system. In addition, tools and equipment used by crews to recover ordnance such as nonsparking shovels and lifting hoists are not necessary when an autonomous machine is used to perform these same functions. However, costs for renting an ordnance transport truck were retained in the estimates. This truck is still needed to periodically visit the site and haul off any recovered ordnance that is left on the periphery of the remediation area by the autonomous equipment.

- Clearing and grubbing of the site was included in the conventional estimates. However, this activity was assumed to not be required with an autonomous system as the equipment is designed to search and locate in more rugged terrain and conditions than conventional crews.

- The Contractor General Conditions model was run using defaults for all autonomous applications except for the following listed below. In the Field Expenses section of the Contractor General Conditions model, the Site Project Manager, Superintendent, Clerks, Vehicles, and Survey Crew manning requirements were set to zero. It was assumed that tasks of a Site Project Manager, Superintendent, Clerk, and Survey Crew would be performed by the Master technician during the site setup and search and recovery phases of the remediation. Since one rental vehicle was retained in the direct cost assemblies, any additional vehicles defaulted by the General Conditions model were therefore not needed and were set to zero. The project durations for the autonomous estimates were determined by adjusting a Safety Level E project duration (five days per week, 40 hours per week of operation) to one of a project progressing at the rate of seven days per week, 160 hours per week of operation

3.2.2.5 Area Clearance Results

Table 6 shows the project duration, staffing requirements, and the number of equipment hours for each of the six scenarios in area clearance. It should be noted that project durations in the General Conditions model of *RACER* are entered in whole months. Therefore, the project durations were rounded to the nearest whole month with a duration of one month being selected as the shortest project duration. This was necessary because a project duration of zero months entered into the General Conditions model will calculate zero costs, i.e., no assemblies. The number of equipment hours in the last row of the table represents the number of hours for which the equipment was being operated in either telerobotic or autonomous mode.

The abbreviations listed in the tables and graphs for the different applications are as follows: CONV-E, conventional means at Safety Level E; CONV-A, conventional means at Safety Level A; TELE-R or P, teleoperated rental or purchase; AUTO-R or P, autonomous rental or purchase.

Table 6 shows the following trends:

- For Low or Moderately Low complexities, the project duration is relatively unaffected by the replacement of conventional crews with teleoperated or autonomous equipment since the staffing requirements are small. However, for complexities of Moderate and above, teleoperated or autonomous application project durations begin to exceed conventional Safety Level E project durations since the estimates were made on the basis that multiple teams were replaced by only one piece of equipment. If the availability of teleoperated or autonomous equipment will be limited in the near future, then conventional removal can be deemed to be preferable if timeliness of the remediation is a driving factor.

- If timeliness of the remediation is not of concern and the decision is made to replace conventional crews with a teleoperated or autonomous system, then these systems are the optimal choice since staffing requirements are reduced at complex sites. The purchased teleoperated option is more expensive than the purchased autonomous option since teleoperated equipment can only be operated during daylight hours.

RACER Results for Low Complexity Scenario				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	1	2	1	1
Master Tech hrs)	160	160	160	160
# of Master Techs	1	1	1	1
EOD Tech (hrs)	320	320	160	0
# of EOD Techs	2	2	1	0
Equipment (hrs)	-	-	160	160
***RACER* Results for Moderately Low Complexity Scenario**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	1	3	1	1
Master Tech (hrs)	200	200	200	200
# of Master Techs	1	1	1	1
EOD Tech (hrs)	400	400	200	0
# of EOD Techs	2	2	1	0
Equipment (hrs)	-	-	200	200
***RACER* Results for Moderate Complexity**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	3	7	9	3
Master Tech (hrs)	480	480	480	480
# of Master Techs	1	1	1	1
EOD Tech (hrs)	2,880	2,880	1,440	0
# of EOD Techs	6	6	1	0
Equipment (hrs)	-	-	1,440	1,440
***RACER* Results for Moderately High Complexity**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	5	12	20	5
Master Tech (hrs)	840	840	840	840
# of Master Techs	1	1	1	1
EOD Tech (hrs)	6,720	6,720	3,360	0
# of EOD Techs	8	8	1	0
Equipment (hrs)	-	-	3,360	3,360
***RACER* Results for High Complexity**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	7	16	48	12
Master Tech (hrs)	2,320	2,320	2,320	2,320
# of Master Techs	2	2	2	2
EOD Tech (hrs)	16,240	16,240	8,120	0
# of EOD Techs	14	14	1	0
Equipment (hrs)	-	-	8,120	8,120
***RACER* Results for Very High Complexity**				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	11	24	100	26
Master Tech (hrs)	3,440	3,440	3,440	3,440
# of Master Techs	2	2	2	2
EOD Tech (hrs)	34,400	34,400	17,200	0
# of EOD Techs	20	20	1	0
Equipment (hrs)	-	-	17,200	17,200

Table 6. Area Clearance Site Complexity Results

Figure 3 illustrates the total *RACER* project costs (escalation included) for each of the six scenarios for area clearance.

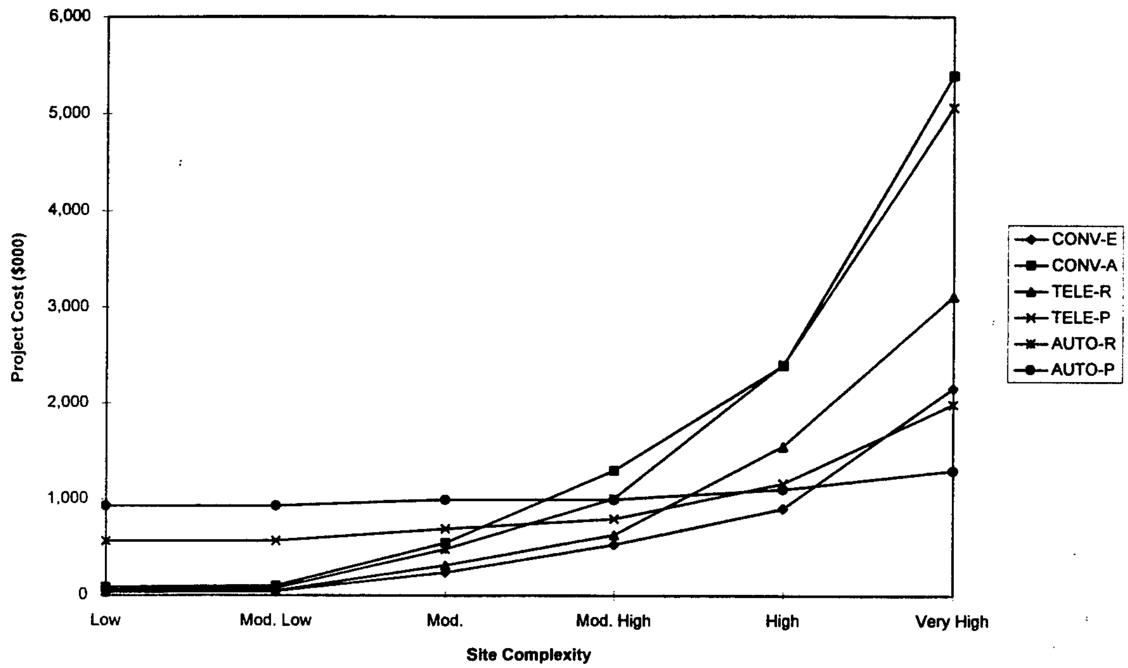


Figure 3: Area Clearance

Table 7 presents the total project costs in thousands of dollars ($000) for each removal application for the six scenarios in area clearance. This is the same data that has been used to plot the graph in Figure 3.

Total *RACER* Project Costs ($000) by Site Complexity						
	Low	Mod. Low	Mod.	Mod. High	High	Very High
CONV-E	30	39	237	530	904	2,148
CONV-A	86	100	548	1,297	2,391	5,391
TELE-R	39	46	315	632	1,547	3,111
TELE-P	565	567	694	796	1,162	1,982
AUTO-R	61	74	483	1,007	2,402	5,064
AUTO-P	931	933	998	998	1,104	1,293

Table 7: Area Clearance Project Costs

Figure 3 and Table 7 illustrate the economy of scale in using a purchased teleoperated or autonomous system to remediate increasingly more complex sites. Once the capital investment has been made to purchase one of these machines, a reduction in labor requirements can be realized. However, for the least complex of these sites, conventional methods remain the least expensive method because of the capital investment required.

3.2.3 Unexploded Ordnance (UXO) Removal Mission

The unexploded ordnance (UXO) removal mission is based on the assumption that all of the search activities have been completed prior to ordnance recovery. As a result, the operations that are performed are solely to recover ordnance from a known location. For the autonomous system, it is assumed that the locations are input into a computer control system allowing an optimized path to be plotted before the recovery operation begins.

3.2.3.1 *RACER* Scenarios for UXO Removal Mission

These scenarios are based on the same information that was used to develop the UXO removal scenarios. UXO removal cost estimates are based on recovery tasks that are required for the scenarios. The methodology and assumptions used in estimating area clearance were also used for UXO removal.

3.2.3.2 Conventional UXO Removal Assumptions

The conventional estimates were made by performing a second *RACER* cost estimate in addition to the search and recovery cost estimates made for area clearance. These estimates were made by using all the required parameters from the area clearance runs except for the Type of Operations parameter. This required parameter was changed from Search and Recovery to Search Only. These new estimates would then reflect the costs to locate and mark ordnance positions on the surface and in the ground. By subtracting assembly quantities for the Search Only mission from the Search and Recovery mission, the resulting quantities would then reflect an estimate for a Recovery Only mission. The following assumptions summarize the methodology used in preparing the conventional removal estimates:

- The number of Master and EOD technicians was kept the same for UXO removal and area clearance. This meant that since work activities were less in UXO removal, because all the search activities had been previously completed, the project durations were less in UXO removal as compared to area clearance. Since the number of technicians was kept the same, individual safety equipment was not reduced since this equipment is still required to enter the site. However, with a shorter project duration, material and equipment that were rented on a periodic basis, such as hand-held GPS units, were reduced in total rental period and cost. Thus, the material and equipment assemblies left in these estimates were those required for recovery tasks.

- All clearing and grubbing activities were considered to occur during the search phase. Therefore, clearing and grubbing costs were removed from the UXO removal estimates.

- The Contractor General Conditions and Overhead and Profit models were run using the same assumptions for UXO removal as they were for area clearance. The only difference between these two runs was the project duration.

3.2.3.3 Teleoperated UXO Removal Assumptions

The teleoperated estimates were performed by using the direct cost assemblies from the conventional runs as a starting point. Next, individual direct cost assembly quantities were adjusted to reflect the assumptions that were made for these estimates. Finally, after the direct cost assembly adjustments were completed, the Contractor General Conditions and Overhead and Profit models were run to generate project costs for each site scenario. The following assumptions summarize how the teleoperated estimates were made:

- In general, the same assumptions were used from the teleoperated area clearance runs; i.e., one of a kind equipment operated 40 hours per week by one EOD technician. The number of machine hours was set equal to one-half of the total number of EOD technician hours required by the conventional UXO runs. Overall, the only difference between teleoperated runs performing UXO removal and area clearance is that the project duration, and hence the work activities, were less in UXO removal as compared to area clearance.

3.2.3.4 Autonomous UXO Removal Assumptions

The autonomous system estimates were performed by using the direct cost assemblies from the teleoperated UXO removal runs as a starting point. Next, individual direct cost assembly quantities were adjusted to reflect the assumptions that were made for these estimates. Finally, after the direct cost assembly adjustments were completed, the Contractor General Conditions and Overhead and Profit models were run to generate project costs for each site scenario. The following assumptions summarize how the autonomous system estimates were made:

- In general, the assumptions used for the autonomous system area clearance runs were applied; i.e., one-of-a-kind equipment operated at a rate of 160 hours per week, independent of any EOD equipment operators. All site oversight and equipment programming duties were to be handled by a Master EOD technician who traveled to the site on a part-time basis over the project duration. The number of machine hours was set equal to the teleoperated runs. Overall, the only difference between autonomous systems performing UXO removal and area clearance is that the project duration, and hence the work activities, were less in UXO removal as compared to area clearance.

3.2.3.5 UXO Removal Results

Table 8 presents the project duration, staffing requirements, and the number of equipment hours for each of the six scenarios in UXO removal. It should be noted that project durations in the General Conditions model of *RACER* are entered in whole months. Therefore, the project durations were rounded to the nearest whole month with a duration of one month being selected as the shortest project duration. This was necessary because a project duration of zero months entered into the General Conditions model will calculate zero costs, i.e., no assemblies. The number of equipment hours in the last row of the table represents the number of hours for which the equipment was being operated either in teleoperated or autonomous mode.

The abbreviations listed in the tables and graphs for the different applications are as follows: CONV-E, conventional means at Safety Level E; CONV-A, conventional means at Safety Level A; TELE-R or P, teleoperated rental or purchase; AUTO-R or P, autonomous rental or purchase.

As with Area Clearance, these UXO removal results show that for Low or Moderately Low complexities, the project duration was relatively unaffected by the replacement of conventional crews with teleoperated or autonomous equipment since the staffing requirements were small. However, for complexities of Moderate and above, teleoperated or autonomous application durations began to exceed conventional Safety Level E durations since the estimates were made on the basis that multiple teams were being replaced by only one piece of equipment. If the availability of teleoperated or autonomous equipment will be limited in the near future, then conventional methods may be deemed to be preferable if completion time for the remediation is a driving factor.

RACER Results for Low Complexity Scenario				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	1	2	1	1
Master Tech (hrs)	160	160	160	160
# of Master Techs	1	1	1	1
EOD Tech (hrs)	320	320	160	0
# of EOD Techs	2	2	1	0
Equipment (hrs)	-	-	160	160
RACER Results for Moderately Low Complexity Scenario				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	1	3	1	1
Master Tech (hrs)	200	200	200	200
# of Master Techs	1	1	1	1
EOD Tech (hrs)	400	400	200	0
# of EOD Techs	2	2	1	0
Equipment (hrs)	-	-	200	200
RACER Results for Moderate Complexity				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	2	4	6	2
Master Tech (hrs)	200	200	200	200
# of Master Techs	1	1	1	1
EOD Tech (hrs)	1,760	1,760	880	0
# of EOD Techs	6	6	1	0
Equipment (hrs)	-	-	880	880
RACER Results for Moderately High Complexity				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	3	6	14	4
Master Tech (hrs)	360	360	360	360
# of Master Techs	1	1	1	1
EOD Tech (hrs)	4,800	4,800	2,400	0
# of EOD Techs	8	8	1	0
Equipment (hrs)	-	-	2,400	2,400
RACER Results for High Complexity				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	5	11	35	9
Master Tech (hrs)	1,600	1,600	1,600	1,600
# of Master Techs	2	2	2	2
EOD Tech (hrs)	11,920	11,920	5,960	0
# of EOD Techs	14	14	1	0
Equipment (hrs)	-	-	5,960	5,960
RACER Results for Very High Complexity				
	CONV-E	CONV-A	TELE-R or P	AUTO-R or P
Project Duration (mo)	9	20	76	20
Master Tech (hrs)	2,600	2,600	2,600	2,600
# of Master Techs	2	2	2	2
EOD Tech (hrs)	26,000	26,000	13,000	0
# of EOD Techs	20	20	1	0
Equipment (hrs)	-	-	13,000	13,000

Table 8: UXO Removal Site Complexity Results

Figure 4 below illustrates the total *RACER* project costs (escalation included) for each of the six scenarios for UXO removal.

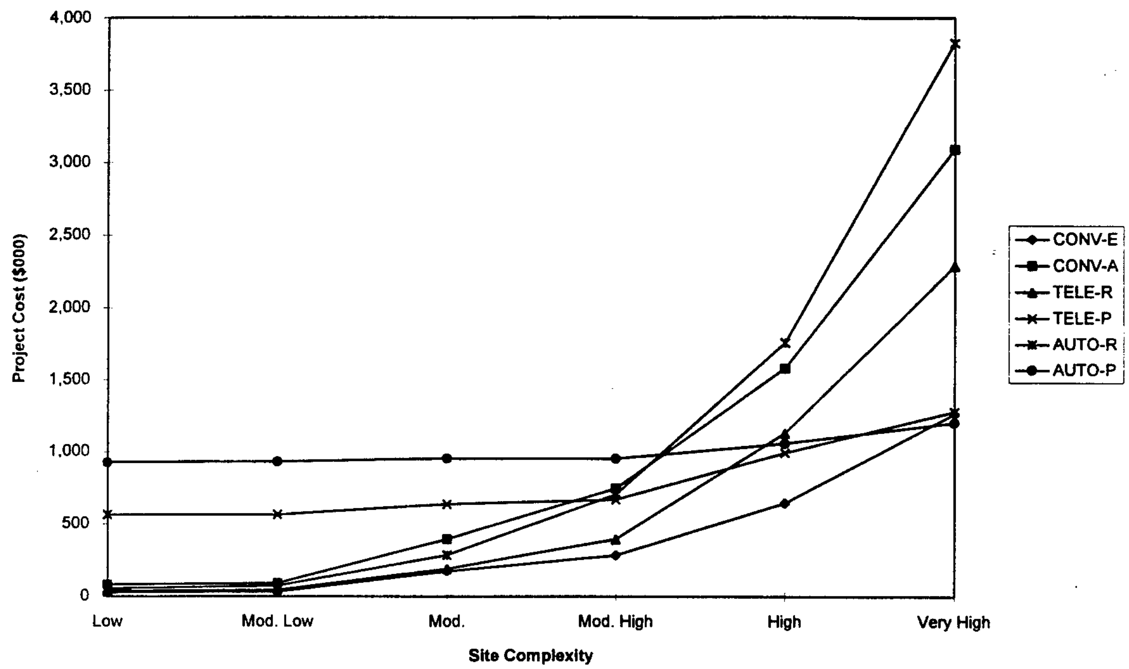


Figure 4: UXO Removal Costs

Table 9 presents the total project costs in thousands of dollars ($000) for each removal application for the six scenarios in UXO removal. This is the same data that has been used to plot the graph in Figure 4.

Total *RACER* Project Costs ($000) by Site Complexity						
	Low	Mod. Low	Mod.	Mod. High	High	Very High
CONV-E	27	32	173	283	644	1,263
CONV-A	82	90	395	746	1,581	3,088
TELE-R	37	44	191	393	1,129	2,288
TELE-P	563	565	635	667	993	1,280
AUTO-R	55	73	284	703	1,760	3,825
AUTO-P	926	932	954	953	1,058	1,201

Table 9: UXO Project Cost Table

The graph and table illustrate the economy of scale in using a purchased teleoperated or autonomous system to remediate increasingly complex sites. The costs for UXO removal are less than the same scenarios in area clearance because search activities have already been performed prior to UXO removal.

3.2.4 Development of Equipment Costs

3.2.4.1 Development of Conventional Equipment Costs

All estimates for conventional operation were produced using *RACER* default quantities and costs. All quantities of work generated in *RACER* models are priced using the U.S. Army Corps of Engineers' (USACE) Unit Price Book. In all conventional estimates, all equipment was assumed to be rented, and default prices for labor, equipment, and material were used.

3.2.4.2 Development of Autonomous and Teleoperated Equipment Costs

Rental and purchase costs were used in the evaluation of teleoperated and autonomous systems' cost effectiveness. Purchase costs were based on information provided by Wright Laboratory and equipment quotes were obtained from Caterpillar. Rental costs were based on hourly ownership and operating costs. These two costs were derived from the purchase prices using procedures prescribed by the USACE.

Ownership costs consist of two elements. The first is an estimate for depreciation of the equipment. The second is an estimate of allowances for interest, insurance, and taxes. This allowance is often referred to as Facilities Capital Cost of Money. Operating costs encompass fuel, filters, oil and grease, scheduled maintenance, and repairs or overhauls. The USACE equipment pricing procedures include two sets of pricing factors, one for average operating conditions and one for severe operating conditions. Rental costs for both telerobotic and autonomous systems were derived using the severe condition factors, which include a reduced service life and result in more conservative hourly operating cost figures.

3.2.4.3 Teleoperated Cat 325L with Extended Boom

The basic equipment used to accomplish teleoperated and autonomous tasks was assumed to be a standard CAT 325L Long Reach Hydraulic Excavator with a 3/4 cubic yard bucket. The excavator was modified through the addition of specialized equipment to facilitate autonomous and telerobotic operation. Purchase prices for the excavator were established at $232,658, with an additional $100,000 required to add teleoperated equipment.

The rental rates for this equipment operating in the teleoperator mode are based on the following assumptions:

- Purchase price of $332,658
- Per USACE guidelines, salvage value was based on 25% of the original purchase price of the excavator itself. The telerobotic equipment was assumed to have no salvage value.
- Based on USACE guidelines, the excavator was assumed to have a 6,500-hour service life based on severe operating conditions.
- Shipping weight is 59,810 lbs
- Operating weight is 63,590 lbs
- Maximum horsepower is 168 hp.

Based on these assumptions and the methodology defined by the USACE, the rental rate calculated for the teleoperated excavator was $116.60 per hour. Total purchase price for this equipment, including sales tax and freight, was $377,878.

3.2.4.4 Autonomous Cat 325L with Extended Boom

The total purchase cost for conversion of the equipment to an autonomous mode was assumed to be $350,000. Using the base equipment cost of $232,658, the total equipment cost for the autonomous system was $582,658. Assumptions used for the development of rental rates for the autonomous equipment were the same as those used in the development of the teleoperated system's rates. The rental rate for this equipment was calculated to be $192.83 per hour. Purchase price for this equipment, including sales tax and freight, was $642,878.

4.0 Conclusions and Recommendations

The purpose of this study was threefold: (1) to develop a methodology for evaluating teleoperated and autonomous systems; (2) to develop a methodology for evaluating the cost benefits in using teleoperated and autonomous systems to remediate unexploded ordnance and hazardous waste; and (3) to provide insight and direction for the research and development of teleoperated and robotic systems. In order to achieve these objectives, fuzzy logic heuristics were used to evaluate the system characteristics, and parametric cost estimating was used to evaluate the remediation costs. This section addresses the elements and approach toward the research and development of these systems.

Fuzzy logic provides a means to analyze data which cannot be expressed numerically. Such data include worker safety, productivity, and accuracy. These are concepts that are expressed verbally. Unlike traditional decision supporting models which are based on numeric data, fuzzy logic facilitates a heuristic analysis based on linguistics. Characterization of telerobotic and autonomous systems through fuzzy logic generates a decision matrix that one can use to evaluate the potential applicability of telerobotic and autonomous equipment based on factors other than cost. The fuzzy logic decision matrix also facilitates the evaluation of potential enhancements to the teleoperated and autonomous systems. Factors identified in the fuzzy logic decision matrix can be evaluated to determine their relative importance (weight factor). Once all the factors are ranked or scored, they can be used to develop performance criteria for telerobotic and autonomous equipment. Characteristics and benefits identified using the fuzzy logic process can be used in conjunction with the parametric cost estimating methodology to thoroughly evaluate the applicability of telerobotic and autonomous equipment to environmental restoration activities.

The initially conservative assumptions employed in the cost estimates were chosen to ensure unbiased comparison of the conventional, telerobotic, and autonomous systems. The assumptions were based on the current capabilities of the equipment. This approach was selected in order to create a level of credibility in the estimates. Actual performance data for telerobotic and autonomous equipment were not available during the execution of this study, thus, it was necessary to make assumptions regarding performance. The validity of the estimates is commensurate with the validity of the assumptions used. Obviously, specific, field-verified performance data will be required to refine these estimates further. The graphs in Section 3 illustrate the situations where teleoperated and autonomous systems are applicable.

The combination of parametric cost estimating and notional analysis using fuzzy logic forms the basis to draw conclusions and further focus research and development efforts. The following section presents multiple research and development alternatives.

The selected format details the type of research and development, then gives examples of study data that can be used to support the research and development direction.

4.1 Suggested Program Direction

4.1.1 Development of Modular Automation Packages that can be Attached to Conventional Equipment

The cost estimating data clearly illustrate that the cost of the equipment for the teleoperated and autonomous systems is the major cost element. In addition, the equipment availability drives the schedule. Increases in project costs resulting from keeping a site operational for multiple years negate the benefits associated with telerobotic and autonomous operation. Through the development of standardized automation modules, conventional equipment could be mobilized to the site and retrofitted with teleoperated or autonomous control modules. Although this concept is ambitious, the process would eliminate the "one-of-a-kind" operational hindrance.

Supporting Data

- Comparison of the data in the tables for Area and UXO Clearance and Hazardous Waste Excavation
- Increased personnel safety
- Reduction in the number of personnel for operation
- Reduced remediation time.

4.1.2 Focus on the Operation of Systems in an Autonomous Mode

Although rather self evident, pursuit of the autonomous operating mode is very beneficial since it offers the highest overall system benefit rating. In addition, as the site complexity increases, the application of these systems becomes more cost effective.

Supporting Data

- Safety of operating personnel
- Lower total remediation costs
- Largest cost element in most cases is personnel costs
- Improved remediation time resulting from almost 24 hour a day operation possible with autonomous equipment
- Risk and uncertainty in the remedial environment.

4.1.3 Limited and Remote Supervision - Focus on Standardization for Controls

This concept refers to the ability to operate automated systems from an off-site location. In this concept, a central control room could operate robotic and telerobotic systems for a base. By centralizing the operations, many economies of scale can be observed (e.g., elimination of redundant control systems, improved personnel utilization, improved working conditions, etc.).

Supporting Data

- Part-time work for the Master EOD Technicians
- More capital resources shared among multiple systems
- Enhanced performance due to improved remote information feedback (i.e., improved remote viewing through better display systems and optimizing the viewing environment, teleoperated system, improved tracking and on-the-fly changes for autonomous systems)
- Improved remediation time.

4.1.4 Focus Research on the Primary Functionalities of the Telerobotic and Autonomous Equipment

All ranges are not created equal. This is briefly addressed with site complexity; however, there are many facets which create thousands of combinations. Each combination of site parameters represents a scenario which has an optimum solution. However, there may not be a set of decision curves, algorithms, or tables that provide this solution. This leads to the general concept of focusing on the primary functionalities of the equipment. Based on the cost analysis curves in Section 3, small, simple sites are typically best suited to conventional methods. As the complexity of the site increases, so does the complexity of the system selection decision.

The operator in the loop is able to adapt to the site conditions. To date, an autonomous system does not have this ability and is consequently less flexible than the teleoperated system. Conversely, mundane, repetitive tasks (e.g., continuous excavation on a large site that is free of buried obstructions) requires little or no flexibility, and consequently, requires little or no human input. Hence, use of teleoperated equipment in such instances would constitute ineffective use of resources. This situation is well suited to an autonomous system. By focusing the research and development for teleoperated systems on flexibility and autonomous systems on repeatability, one can achieve increased productivity at reduced remediation costs. This is illustrated in the cost curve data and meets three of the four highest selection criteria in the fuzzy logic analysis.

Supporting Data

- Fuzzy Logic Decision Support System (top 3 out of 4 H+ ratings)
- Cost curve analysis
- More efficient use of resources.

4.1.5 Focus on Operating in Extremely Hazardous Environments

Operation in an extremely hazardous environment creates situations where conventional remediation techniques are impeded by safety requirements. These cases can be identified as Safety Level C or higher operating conditions, and for explosive, radioactive, and mixed waste sites (combination of hazardous and radioactive wastes). The productivity of the operator is reduced, and in the case of radioactive exposure, can result in people exceeding their annual exposure limit.

These scenarios may require that remote operation or an automated option be employed due to the exposure. Thus, any research and development efforts toward improving the performance of teleoperated and autonomous equipment in extremely hazardous environments will further increase the cost effectiveness and applicability of these systems over conventional equipment.

Supporting Data

- Safety of operating personnel
- Improved equipment productivity
- Increased equipment performance reliability
- Lower total remediation costs.

4.1.6 Sensor Feedback, Display and Control Systems

The development of improved feedback and control systems increases the performance of the teleoperated and autonomous systems. This is more applicable to teleoperated systems than to autonomous systems. Feedback includes audio, video, and sensory input. This information leads to improved performance. As the performance of these systems increases, the cost effectiveness increases.

Supporting Data

- Improved performance
- Reduced remediation cost
- Lower total remediation costs
- Technology push.

4.1.7 Hybrid Development - Combination of Teleoperated and Autonomous System Characteristics

Teleoperated systems have the advantage of adaptability. This characteristic is gained due to the human interface. As the remediation process changes, the human element can adjust to the operating conditions. Remediation processes require many complex operations and adaptation to conform to those conditions. This may be combined with the abilities of automated systems to develop hybrid systems. For example, the first several feet of overburden could be excavated autonomously, and the ordnance could then be removed telerobotically. In this example, the primary strengths or functionalities of both systems are fully utilized.

Smaller teleoperated equipment could be developed for smaller sites and for work in areas with dense vegetation. These two site characteristics demonstrate that the utilization of large equipment has limitations.

Supporting Data

- Decreased capital costs
- Lower total remediation costs
- Safety of operating personnel
- Lower total remediation costs
- Technology push.

4.1.8 Focus on the Operational Efficiency Improvements

Improvements in operational efficiency include improvement in ordnance-locating devices for rapid analysis of areas and development of ordnance-handling tools for the removal of heavy bombs.

Supporting Data

- Safety of operating personnel
- Lower total remediation costs.

4.2 Summary

The development of autonomous systems should focus on the remediation of larger, more complex sites, and the development of teleoperated systems should focus on remediating smaller sites with high degrees of variability. Autonomous systems yield two distinct benefits in dealing with large sites. The first is the reduction in work force required to perform the task in the same time frame. The second is the thoroughness of the robot in recovering a high, or large, percentage of the ordnance. These two features reinforce the concept of robots for complex sites with minimal vegetative cover.

Teleoperated systems have the benefit of reducing labor requirements; however, they cannot compete with autonomous systems from a cost perspective. The advantage of a teleoperated system over an autonomous system is the operator's ability to handle obstacles and changing circumstances. These systems can be used for complex sites, however, they are best suited for smaller sites. Research and development there should focus on the control and feedback systems and the reliability of the machines. Also, the focus should turn to the preprogramming of robotic functions that can be used with teleoperated systems.

Appendix 1

A Brief Description of Various Robots

Introduction

The goal of this section is to provide a brief description of the robots used by the military and private sector. The trend in hardware development is toward "smaller" and more portable units with "lower cost" and "higher efficiency". One example is the Twin-Screw Minesweeper. The U.S. troops in Bosnia are planning to use the Twin-Screw Minesweeper soon for clearing paths through minefields with this unique remote-control robot. The robot was developed at the Lawrence Livermore National Laboratory. It is small and portable. Dubbed the Spiral Tube All Terrain Robot, the low-cost device is based on the Archimedes screw principle. Two tillers turn in opposite directions to move the robot backward or forward across any terrain, including mud and water. Turning the tillers the same direction provides sideways travel, and rotating the tillers at different speeds produces turns. The robot travels at 133 ft. per minute sideways and 20 ft. per minute forward or backward. The device is attracting international interest. The screw-type robot is powered by two DC motors, and it is tethered to an electric generator. Other automated units collect in this study are:

Robots for Inspection

A robot for inspecting bridge supports in dangerous waters was developed by the Sonsub in Houston, TX. Operators review measurements and readings sent by the remotely controlled robot for possible problems with a bridge's foundation. The robots can also perform routine maintenance and repairs.

Innovative Technology: Cutting Wood

A new imaging machine, developed at Virginia Tech in Blacksburg, Va., not only grades furniture-bound hardwood, but also decides the most efficient way to cut the wood, and then cuts it. Hardwood boards are fed into the 10 foot-long machine, where they travel through three stations. A high resolution color camera inspects the wood's appearance and grain; a laser camera measures surface contours to judge its texture, and an X-ray scanner seeks interior defects. During the process, the board's exact dimensions are computed. That data is sent to a computer that identifies the board and grades its quality. Then, checking its preprogrammed memory for instructions on how to handle such wood, the computer directs an automated saw to cut the board. The imaging machine has enormous potential. It allows the operator decide what to do with a board in the middle of the process rather than at the end of the process.

Robot for Space Shuttle Maintenance

Each time the shuttle touches down, a swarm of heavily clad technicians must inspect and water-proof all of the spacecraft's 17,000 thermal-protection tiles. This is a long, arduous, repetitive task that is ideally suited to robotic application.

The Tessellator robot was built at Carnegie Mellon University. Recently delivered to the Kennedy Space Center, the robot scoots about the shuttle, raising and lowering its work platform. Its tool-kit includes a scanning laser, an inspection camera and a waterproofing injector. By comparing each tile against records in its database, the Tessellator can detect defects and erosion. The Tessellator wheels beneath shuttle, expanding and contracting, to eye the spacecraft's underbelly.

Space Robot: Moon Rover

The Moon Rover robot was developed by LunaCorp, which plans to recoup its revenues by selling the means for controlling the rover to theme parks, television networks and science museums. Potential customers could use telepresence technology to guide the rover around the Moon, watching live images from the vehicle's stereo TV cameras. Others would use virtual-reality hardware to simulate a moonwalk based on 3-dimensional terrain maps relayed earlier from the rover.

Robot for Manhole Maneuverer

This robot is designed primarily for electricutility applications. Kraft Tele-robotics in Overland, KS has developed the MS-A Scout to inspect underground transformer vaults if dangerous conditions are suspected. The machine can measure gases, detect temperatures, and relay color video images to human co-workers on the surface. The Scout can maneuver through tight spaces, panning and tilting its color TV camera to inspect utility vaults.

Automated Ditch Digger

Battelle and Concept Engineering Group in Columbus, OH developed a new trenching machine for the Electric Power Research Institute. Called the Soft Trencher, the vehicle extends an excavation head that shatters hard soil by firing supersonic air jets into the ground. A vacuum system removes the soil as it becomes airborne. As it works, the vehicle rolls continuously, opening deep trenches as fast as 1 ft. per minute. The operator can either perch on the driver's seat or run the machine via remote control. Conceived to aid in the burial of power-transmission cables, the Soft Trencher is well suited to urban areas where underground utility lines exist in abundance. The Soft Trencher breaks up earth with air jets, then vacuums loosened soil without harming buried pipes.

Small Downhole Robot

This downhole robot is used at test ranges for non-nuclear explosives at Lawrence Livermore National Laboratory. Because environmental rules protect animals, the lab must monitor the burrows to determine if special precautions are necessary during blasts. The Miniature Optical Lair Explorer, or MOLE, developed in Livermore, CA does just that. The 5-in vehicle carries a small camera that transmits images through an 18-ft cable. Rolling on tracks resembling those of a toy tank, MOLE illuminates the animals' tunnels with red light-emitting diodes. So far the animals haven't reacted aggressively against the robot.

Space Robot

Mc-Donnell Douglas, NASA researchers, and several universities believe the time is right to try a robot on the Moon. The 6-wheeler will handle the Moon's harsher temperature swings. Scientists would gain experience with the virtual-reality telepresence system developed at NASA's Ames Research Center. Control commands and feedback from the robot would transmit between the Earth and the Moon in only 3 seconds.

Robot for Environmental Restoration Sites

As the military turns over real estate to civilians, it has an obligation to dig out buried hazards; anything from old bombs to barrels of waste. A unique vehicle has been developed to assist in the location of buried waste. Called the Surface-Towed Ordnance Locator System, the robot travels along at 3.5 mph, driven by a Volkswagen engine. Behind it trails an array of metal-detecting magnetometers. Positioning data from a GPS receiver converts the sensors' outputs into a map of magnetic anomalies. Geo-Centers Inc. in Newton, MA is now marketing the vehicle for civilian waste dumps. The sensor-towing car is built of aluminum and composites of low magnetic signature.

Satellite Repair Robot

This robot, known as Ranger, is applicable for servicing maljunctioning sattelites that are inaccessible to space-walking shuttle astronauts. In 1996, RAnger will rocket into orbit and rehearse a satellite-servicing mission. The University of Maryland is building the unit for NASA. Once Ranger is spaceborne, remote-control operators will have the robot reach back to the rocket's upper stage and swap some components. If those experiments work out, Ranger will then detach from the upper stage and maneuver freely, performing more repair jobs on the fly. If time permits, the robot will test a novel propulsion system. Ranger's maneuvering jets spew cold nitrous oxide. To change the robot's orbit, a larger thruster will tap the same nitrous oxide as the oxidizer for a hybrid rocket engine. Ranger will practice remote-control satellite-repair motions on its own upper-stage rocket booster.

Robots for NASA

Robots in NASA facilities must operate around humans and sensitive flight hardware. To minimize unforeseen collisions, Merritt Systems Inc. has designed a kind of skin for robotic limbs. Called SensorSkin, the material is a flexible circuit board embedded with three different kinds of proximity sensors. These tiny devices communicate with each other and send data to the robot's control electronics. The skin can be custom tailored and wrapped around the robot in a single piece.

Robot for Fire Fighting

A new way to kill a fire is to disrupt the combustion process mechanically. A new company called FAV Inc. in San Diego, CA is proposing a vehicle to do just that. Dubbed Firecat, the machine is a highly modified excavator equipped with a unique fire-destroying mechanism. At the end of the excavator boom stretches a 20-ft T-bar. Along the bar lie the fire-destroying mechanisms: flailing chains, blades, or brooms, depending on blaze conditions. These devices pulverize burning material and cast it back into the hot side of the fire line, creating a firebreak as the Firecat advances. Although the vehicle's cabin will lie several dozen feet from the flames, it is armored with fireproofing material borrowed from the nuclear power industry. The operator will watch a radar display that provides a 3D view of the surrounding terrain, while an infrared camera peers through a periscope to locate hot spots. FAV has field-tested the slashing mechanisms and is negotiating with equipment suppliers.

Space Walker Robot

Extravehicular activities, or EVAs, will play a big role in future spaceflight. The International Space Station could take 888 EVA hours to assemble, and NASA doesn't want to send any more astronauts outside than it has to. So to give spacewalkers a mechanical sidekick, the Johnson Space Center is developing an EVA Helper/Retriever. The robot will have stereo camera eyes mounted on a pan-and-tilt unit. Its hands will be 3-fingered devices that can snatch objects as they float weightlessly. NASA has tested the dexterity of the robotic hands on recent flights aboard the gravity-defying KC-135 aircraft. Most of the time, the robot will cling to external spacecraft structures with a grasping foot mechanism. Another version could aid astronauts with tasks in the cabin. Engineers hope to put the robot into action by 1998. The two-fisted EVA Helper/Retriever will assist space-walking astronauts during extensive activities.

Underground Excavation Robot

Automated Mining Systems (AMS) Inc., of Toronto, hopes to develop the technology to operate a mine from the surface. Currently, at an Inco nickel mine near Sudbury, Ontario, one man maneuvers two vehicles with an AMS radio-control system. The machines are front-end loaders called scoop trams. They shuttle rock from the working face to a shaft that leads to a crusher. Each tram runs autonomously for three-fourths of the time, with the operator taking control only when it loads and dumps. Inco believes that a single worker could ultimately run four vehicles at once via remote control. Pierced coaxial cables riddle the mine, carrying signals from the surface and broadcasting them to the trams. In the autonomous mode, the vehicles simply follow strings of lights. A semiautonomous robotic scoop tram ferries 12-ton loads of rock between the mine face and a crusher.

NASA's Tele Robot

Since robots are likely to set foot on other planets before humans, NASA wants its mechanical explorers to be as capable as astronauts. Toward that end, Johnson Space Center engineers have created a Dextrous Anthropomorphic Robotic Testbed, or DART. The system allows unprecedented control of a complex human-like robot arm. Instead of joysticks, DART uses a pair of gloves fitted with sensors that read arm, hand and wrist movements. The ambidextrous robot mimics these movements. A head-mounted display shows images from the stereo color cameras that serve as the robot's eyes.

Ordnance-Handling Robot

The Omni-Directional Ordnance Handler was recently tested at the Naval Surface Warfare Center, in Panama City, FL. Developed by a Swedish inventor in the 1970s, the vehicle moves on four unconventional 18-in. wheels. Elliptical rollers, offset by 45°, encircle each wheel hub. A computer controls the rotation speed of each of the wheels independently to turn the vehicle precisely or to change its fore/aft orientation while moving. The Omnidirectional robot pirouettes on wheels ringed with canted, keg-shaped rollers.

Telerobot for Hazardous Waste Sites

To remediate nuclear sites, the U.S. Department of Energy recently has been evaluating a versatile family of little construction robots. Called the HazHandlers, the 10-ft.-long—radio-control vehicles come from Robotech Industries. Each HazHandler rolls on a modified all-wheel-drive Bobcat chassis, propelled by a 40-hp diesel. The vehicle can wield a wide range of attachments, from a bulldozer blade to a barrel grappler to a 7-axis manipulator arm. Supported on a shoulder harness, the control panel sports joysticks and a TV screen that receives images from a camera on the HazHandler. The operator can run the vehicle from as far away as 1000 ft. The remote-controlled HazHandler can accept a variety of standard tools to work in hazardous environments.

Robot for Cleanup of Hazardous Waste

Developed by Sandia National Laboratories, the telerobotic machine uses sensors, automatic planning software, and a GPS-based location system to locate contaminated material and then excavate. Called the Remote TeleRobotic Vehicle for Intelligent Retrieval (RETRVIR), the robot was originally developed to aid in the cleanup of hazardous waste. But RETRVIR has proved a most versatile testbed. For example, it has built a small steel platform almost entirely under its own autonomous control.

Robot for Maneuvering Trailers

This robot is being developed at Rensselaer Polytechnic Institute (RPI). The CATmobile (named for RPI's Center for Advanced Technology) carries sensors to measure jackknife angles, steering angles, and other conditions. An on-board computer then predicts the vehicle's movement and feeds back data to guide the robot through a perfect path. With a few adjustments, the system could aid truck drivers with difficult maneuvers, as the CATmobile is capable of negotiating tight spaces.

Ordnance Neutralization Robots

The Navy's Explosive Ordnance Disposal Technical Center, in conjunction with Pacific Northwest Laboratory is designing the Remote Ordnance Neutralization System, or RONS. The machine rolls on twin sets of tracks, which can lie flat to cross trenches or fold up for tight turns. The robotic arm on RONS will disarm anything from a live shell to a terrorist's bomb. At its disposal will lie tools ranging from wire-cutters to waterjets. The remote operator will sense the tools' efforts through a force-feedback manipulator. Commands and feedback will travel either via radio control or by fiber-optic link if radio energy threatens detonation. This bomb-defusing robot uses pivoting tracks to handle stairs.

Under Water Inspection Robot

Faced by a need to visually inspect three 6,000 ft tunnels between the upper and lower reservoirs of its pumped-storage power station in rural Bath County, Va., Virginia Power developed a remotely operated diving robot that is saving the utility millions of dollars. Leakage from the bored tunnels has been a problem ever since the $1.7-billion, 2,100 Mw project began operating. Substantial outflow continues despite efforts to plug leaking cracks with grout. The tunnels had not been inspected since the grouting program was carried out just before the six-unit station began operating. Engineers preferred to view them while filled with water to determine more accurately where most leakage occurs. Sending divers or manned submersible equipment down some 1,300 ft into the 28 1/2-ft-diameter shafts and across almost a mile to the power plant would have been unsafe, and off-the-shelf robots like those used in offshore oil projects lacked horizontal maneuverability and other necessary features. Virginia Power worked with diving consultant Drew Michel of Royal Technology Inc. to write specifications. It then contracted with International Submarine Engineering Ltd., Vancouver, B.C., to produce the vehicle, which is about the size of a clothes washer. The diving robot is designed to plunge down as deep as 10,000 ft but not wander much horizontally. It goes down only about 1,300 ft. but then goes out 5,000 ft horizontally. That requires, among other things, a 7,000-ft umbilical cord that does not catch on the elbow of the tunnel. It was made by a British firm, Jacques Cable Systems Ltd. The Hydrover is maneuvered by four hydraulic thrusters that can propel it as fast as 90 ft per minute. It has a gyrocompass that is not affected by steel tunnel liners and reinforcing. High-resolution sonar tracks the vehicle's position and helps plot precisely where leakage occurs. The robot is fitted with cameras that rotate around it to inspect the tunnel and save hours in maneuvering time. Another camera with two lenses creates a three-dimensional image. Additionally, a dye-release system helps determine which cracks water is flowing through. It cost about $1 million to design, build, and test the Hydrover. However, that is only a fraction of the cost of shutting down and dewatering the plant and purchasing replacement power at a cost of $1 million to $2 million a day.

Appendix 2

A Blank Sheet of the Fuzzy Logic for Decision Support System in Evaluating Robotic and Telerobotic Systems to Perform Environmental Remediation

Fuzzy Logic for Decision Support System in Evaluating Robotic and Telerobotic Systems to Perform Environmental Remediation (Impacts on the goal)

Factors impacting on goal of a mission for various operating systems	Weight Factor (w)	Operation Systems			
		EOD Base Line Team	Man-operated Machine	Tele-robotics Machine	Autonomous Machine
Socioeconomic and Technology Factors					
Increasing personnel safety					
Improving productivity (see note 1)					
Increasing comfort of the working environment					
Reduces number of personnel needed for operation					
Increases performance reliability (see note 2)					
Increases the Air Force's technological capability in automation and robotics					
To contribute to the Joint Robotics Program established by the DOD					
Reduce environmental impacts					
Improves thoroughness and mission accomplishment (see note 3)					
Increases consistency and accurate characterization					
Leverage manpower and assets					
Reduce overall range clearance time					
Increases the dual use applications that transfer Wright Lab's automation technologies to other governmental agencies and to private industry					
Current level of knowledge about the system (see note 4)					
Degree of interest in the Air Force to develop the system					
Ease of technological issues associated with the system					
Degree of confidence in the life expectancy of the system (see note 5)					
Degree of human expertise needed to do the work (see note 6)					

Fuzzy Logic for Decision Support System (cont.)

Factors impacting on goal of a mission for various operating systems	Weight Factor (w)	Operation Systems			
		EOD Base Line Team	Man-operated Machine	Tele-robotics Machine	Autonomous Machine
Operational Factors					
Capability of the system to work on bad topography					
Capability of the system to work at inaccessible locations					
Effectiveness of the system to work on the large size sites					
Capability of the system to work in bad weather					
Capability of the system to work in dark					
Capability of the system to work 24 hours continuously					
Capability of the system to maneuver quickly					
Degree of overhead insurance reduction					
Total Evaluation for each Operating System Based on Weight Factors					

Key:

H: High M: Medium L: Low +: Above -: Below

NOTES: Clarification for factor definitions.

1. Productivity is defined as cubic yards of dirt moved per hour by the different options. This definition does not account for multiple shifts or multiple pieces of equipment. The higher scores are based on the premise that a skilled excavator operator can achieve the same or higher levels of productivity than an autonomous excavator with sensor systems.

2. Performance reliability is the likelihood that that the option will accomplish the work/mission assigned. This definition does not include the mechanical reliability of the machines. The moderate score on the man-operated machine is based on an excavator without the supporting sensor suite found on the robotic systems. The telerobot is scored slightly higher because of operator's decisions may improve overall reliability.

3. Thoroughness and mission accomplishment includes combat effectiveness for combat missions.

4. Current level of knowledge about the system scores lower against newer technologies because of the unfamiliarity and lack of training when bringing any new technology to practicality.

5. Degree of confidence in the life expectancy of the system takes into account the rapid advance of technologies. That is, the robot technology will advance rapidly making the life expectancy short for any robotic option.

6. Degree of human expertise and training needed to maintain preficiency and safety will be higher in the manned systems.

Appendix 3

Mathematical Theory of

Fuzzy Sets

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Construction Risk Assessment by Linguistics

ROOZBEH KANGARI, MEMBER, IEEE, AND LELAND S. RIGGS

Abstract—Most construction risk analysis models are based on quantitative techniques which require numerical data. However, in many cases, the available information related to uncertainty factors is not numerical. Rather this information can be expressed as words or phrases in a natural language. These words or phrases are termed linguistic variables and can be provided by practitioners in a given field. This paper outlines an approach to the assessment of project risk by linguistic analysis using fuzzy set theory.

Key Words—Construction; fuzzy sets; linguistics; project management; risk analysis; uncertainty.

I. Introduction

THE CONSTRUCTION industry has a very poor reputation for coping with risk. Risk analysis is either ignored or done subjectively by simply adding a contingency. As a result many major projects fail to meet schedule deadlines and cost targets with an attendant loss to both contractors and owners.

But as construction projects become more uncertain and complex, the need for risk management has increased. This need is particularly significant when projects involve large capital expenditures, new technology, unbalanced cash flows, and complex legal and contractual arrangements. This is not to say that a comprehensive risk analysis will prevent cost and schedule overruns but, at least, it will give managers a more rational basis on which to make decisions.

The purpose of this paper is to introduce the concept of construction project risk analysis by fuzzy set theory and to provide a methodology for risk assessment by linguistics. As will be described, the use of fuzzy sets will allow an analyst to communicate degrees of risk of individual project elements to people in readily understood language terms. Once these individual risk elements are communicated, fuzzy set theory would then permit an evaluation of the overall risk of a construction project.

Most existing risk analysis models are based on quantitative techniques which require numerical data. However, much of the information related to risk analysis is not numerical. Rather, this information is expressed as words or sentences in a natural language. When information about risk is captured in natural language, the words are termed linguist variables and can then be analyzed using fuzzy set theory.

Although linking fuzzy set theory with risk analysis is still in the research stage, one promising area for practical application is in knowledge-based expert systems. For example, fuzzy set terminology can be used to construct a friendly user interface with the expert system. In other words, instead of requiring the user to input a numerical data in response to a query by the expert system, the user can input a response in natural language fashion such as "high," "medium," or "low." This type of interface could be valuable to those parties (owners, contractors, lenders, bonding and insurance agents) who have a stake in evaluating the risk of a project.

Another application area might be in voice communication with computers. Again, fuzzy set terminology would permit an inexperienced person to communicate in natural language and have the responses processed by sophisticated decision analysis computer models.

II. Background

Extensive reserch has been done in evaluation and management of risk. Kahneman *et al.*[12] have discussed in detail the issues of judgement under uncertainty and application of heuristics in risk analysis. Covello *et al.*[7] have presented various methods of risk assessments. Kunreuther and Ley [16] have discussed risk assessment in a problem context, decision processes, and prescriptive aspects of risk, and a list of future research needs is provided. Lichtenstein *et al.* [18] have presented a general framework for dealing with problems under uncertainty. Various risk assessment models, case studies related to risk management, legal issues, and research needs are described by Waller and Covello [22]. Major issues in risk management, ethics, and values in risk analysis are explored in detail by Whipple and Covello [23].

Research has also been done in the area of fuzzy sets. In 1965, Zadeh [25]–[27] introduced the concept of a fuzzy set as a model of a vague fact. Fuzzy set theory is a generalization of ordinary set theory and provides an adequate conceptual framework as well as a generalization of ordinary set theory and provides an adequate conceptual framework as well as a mathematical tool to solve real world physical problems which are often obscure or indistinct. Zadeh's analysis led him to two basic observations. First, humans have a capability to understand and analyze imprecise concepts which are not easily incorporated into existing analytical methods. Second, current methodologies show a concern for precise representation of certain system aspects that are irrelevant to understanding the system's objectives.

Since its inception, the theory of fuzzy sets has evolved in many directions, and is currently finding applications in a wide variety of fields [5], [8], [13], [17], and [19]. The application of fuzzy sets to construction engineering and management, however, has not yet been fully explored. Ayyub and

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The authors are with the School of Engineering, Georgia Institute of Technology, Atlanta, GA 30332.

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Haldar [1] applied fuzzy set concepts to construction project scheduling. In another paper, Nguyen [20] applied the theory to a decision model for selecting bid contracts. Koehn [15] worked on the utilization of fuzzy sets to the complex problems of building or facility satisfaction and productivity on a construction site. However, no significant work in construction risk analysis by fuzzy sets has been conducted. The purpose of this paper is to provide a basic framework for the utilization of the theory in construction risk evaluation.

III. Risk Evaluation Techniques

There are various methods of risk evaluation of construction projects. In general, they can be categorized as: 1) classical models (i.e., probabilistic analysis); and 2) conceptual models (i.e., fuzzy set analysis). Some of the probabilistic factors affecting a construction project are data based. That is, sufficient numerical information is available for a statistical characterization of these factors. However, some other probabilistic factors do not have enough information to develop a statistical pattern. They need to be updated as information becomes available. In this case, the statistical Bayesian updating approach can be used.

Although these classical models are useful for risk analysis, they are limited in their applicability to real construction risk analysis where many of the contractor's decision problems are imprecise, ill-defined, and vague in nature. The imprecision, ill-definedness, and vagueness that tend to characterize various construction problems are predominantly subjective and linguistic in their nature.

In the real construction world, there are many situations where the quantitative and detailed information to evaluate uncertainty is not available. These conceptual factors can be expressed in qualitative or linguistic terms, that is, so called fuzzy information. Uncertainty factors such as "bad weather," "poor design," or "weak management" fall into this category [2] and [14]. Direct analysis of these linguistic factors are often neglected in classical construction risk analysis techniques. This paper attempts to establish the basic feasibility of using fuzzy set concepts in construction risk analysis. Certain simplifications have been made to facilitate understanding of the most important features of the theory. One simplification is that the proposed model is for a limited range of risks in order to keep discussion manageable. Moreover, risk analysis of hazards which combine very low probability and very severe consequences is not within the scope of this paper. Readers are referred to Perrow's [21] approach for this type of system accident analysis.

IV. Fuzzy Set Analysis

Fuzzy set analysis of risk allows a linguistic approach to risk evaluation of projects based on natural language expressions by linguistic variables. A linguistic variable is a variable whose values are not numbers but words or phrases in a natural or synthetic language. Thus, each word x in a natural language can be viewed as a summarized description of a fuzzy set $A(x)$ of a universe of discourse U, which $A(x)$ represents the meaning of x. Linguistic variables and fuzzy sets have the relationship of goal and tool. Manipulating linguistic variables is the goal, and fuzzy set theory is a tool to achieve that goal.

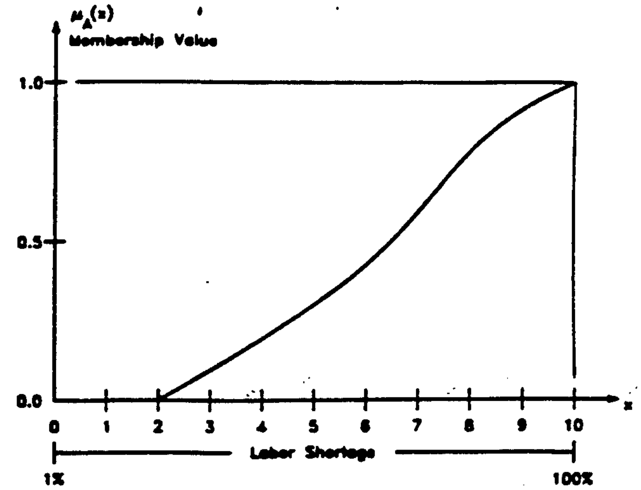

Fig. 1. Fuzzy set graph of labor shortage.

Fuzzy sets can be expressed mathematically as follows:

$$A = [x|\mu_A(x)] \tag{1}$$

where A = fuzzy set; $\mu_A(x)$ = membership value between zero and one; and x = a scale element between zero and ten. For example, if the meaning of the term "severe labor shortage" is expressed as a fuzzy set, the set might take on membership values as follows:

$$A(\text{severe labor shortage}) = [0|0., 1|0., 2|0., 3|0.1, 4|0.2, 5| \cdot 0.3, 6|0.4, 7|0.6, 8|0.8, 9|0.9, 10|\ 1.0]. \tag{2}$$

The positions of the elements in the arrays represent corresponding points in the universe of discourse. The number represents degree of membership of these points. In this way, the meaning of linguistic values as fuzzy sets of an appropriate psychological continuum can be modeled.

The fuzzy set shown above represents the user's understanding of the linguistic variable "severe labor shortage." In this fuzzy set, 10 has a strong membership value of 1.0, and 7 has a weaker membership value of 0.6. In the context used above, the values 0 through 10 might correspond to the amount of laborers short where 0 is no shortage and 10 is a total shortage.

The fuzzy set representing "severe labor shortage" could also be depicted graphically as shown in Fig. 1. In this figure, the x axis indicates a shortage index from 0 to 10 and the y axis indicates the membership value which is similar to a weight factor. Also, the 0 to 10 axis might map to a shortage axis where 0 reflects a 1-percent shortage and 10 reflects a 100-percent shortage.

The idea behind these curves is to represent the gradual transition of linguistic variables as realistically as possible and to avoid sudden jumps at any given value. One approach to construct fuzzy sets for linguistic variables is shown in Fig. 2. In this example, the objective is to evaluate three fuzzy sets to describe total risk of a project. Here, "risk" is a linguistic variable; "high," "medium," and "low" are the fuzzy restrictions. The combination of a linguistic variable and a

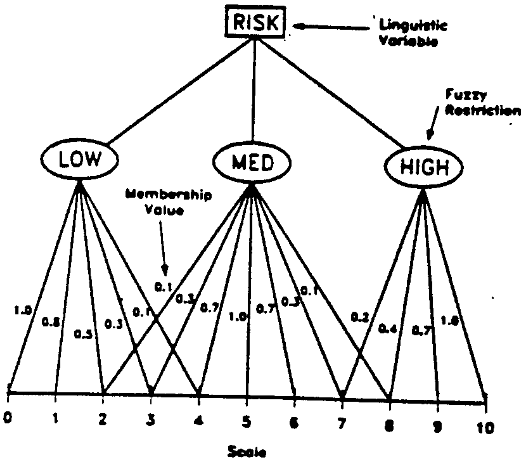

Fig. 2. Structure of fuzzy set analysis.

fuzzy restriction becomes a fuzzy set (e.g., "medium risk").

To develop a fuzzy set, first the decision maker (DM) or system designer identifies the linguistic variable and fuzzy restrictions as shown in Fig. 2. Then each fuzzy restriction is linked to a numerical value on a scale of zero to ten which represents the level of risk. For example, zero is the lowest expected level of risk and ten is the highest. Next, a membership value between zero and one is assigned to each branch coming out of the fuzzy restrictions. These values show the DM's degree of belief in a given level of risk on the scale. To illustrate, in Fig. 2, the DM believes 100 percent (shown as membership value of one) that number 5 on the scale represents his highest level of the word "medium;" and he believes 30 percent that number 7 on the scale defines "medium." Therefore, the fuzzy set representing "medium risk" can be shown as:

$$\text{Medium Risk} = [0|0., 1|0., 2|0.1, 3|0.3, 4|0.7, 5| \cdot 1., 6|0.7, 7|0.3, 8|0.1, 9|0., 10|0.]. \quad (3)$$

Other techniques for determining the user's preference for membership values in a fuzzy set are described in references [3], [4], and [9].

V. Linguistic Approach to Risk Assessment

Our proposed linguistic approach for construction risk analysis uses Zadeh's extension principle. The extension principle results in the following definitions of fuzzy addition, multiplication, and division. If A and B are two fuzzy sets as follows:

$$A = [x|\mu_A(x)] = [0|1.0, 1|0.6, 2|0.2] \quad (4)$$

$$B = [y|\mu_B(y)] = [0|0.1, 1|0.5, 2|1.0] \quad (5)$$

in which x and y = elements of universe X, and universe Y, respectively. In this example, the x scale has been limited to values of 0, 1, and 2 for simplicity. Now:

$$\begin{aligned} A \bullet B &= [(x+y)|\min(\mu_A(x),\ \mu_B(x))] \\ &= [(0+0)|0.1, (0+1)|0.5, (0+2)|1.0, (1+0)|0.1, \\ &\quad \cdot (1+1)|0.5, (1+2)|0.6, (2+0)|0.1, (2+1)|0.2, \\ &\quad \cdot (2+2)|0.1] \\ &= [0|0.1, 1|0.5, 2|1.0, 3|0.6, 4|0.1] \end{aligned} \quad (6)$$

$$\begin{aligned} A \odot B &= [(x \times y)|\min(\mu_A(x),\ \mu_B(y))] \\ &= [(0\times 0)|0.1, (0\times 1)|0.5, (0\times 2)|1.0, (1\times 0)|0.1, \\ &\quad \cdot (1\times 1)|0.5, (1\times 2)|0.6, (2\times 0)|0.1, (2\times 1)|0.2 \\ &\quad \cdot (2\times 2)|0.1] \\ &= [0|1.0, 1|0.5, 2|0.6, 4|0.1] \end{aligned} \quad (7)$$

$$A \ominus B = [(x \div y)|\min \mu_A A(x),\ \mu_B(y))] \quad (8)$$

in which $\bullet$, $\odot$, $\ominus$ are fuzzy arithmetic operations of addition, multiplication, and division of two fuzzy sets; and $+, \times, \div$ are the normal arithmetic operations. When the result of calculation leads to more than one membership value for a given scale, the highest membership value is selected. In most cases, $A \ominus B$ must be approximated. One approach is to reduce this set by disregarding any number from the division operation that is not integer [6], [8], and [27]. A numerical example for fuzzy division is shown later.

Our risk analysis model consists of three parts: A) natural language computation by fuzzy set theory; B) fuzzy set evaluation of risk; and C) linguistic approximation. All are discussed below.

A. Natural Language Representation

Consider a set of natural language expressions that term "management" can take as: "poor," "average," and "excellent." Then the fuzzy sets of these expressions based on integers between zero and ten can be presented as follows:

$$\text{Poor Management} = [0|0.8, 1|1.0, 2|0.7, 3|0.4, 4|0.1, \cdot 5|0., 6|0., 7|0., 8|0., 9|0., 10|0.] \quad (9)$$

$$\text{Average Management} = [0|0.0, 1|0., 2|0.2, 3|0.5, 4|0.8, | \cdot 5|1.0, 6|0.8, 7|0.5, 8|0.2, 9|0., 10|0.] \quad (10)$$

$$\text{Excellent Management} = [0|0.0, 1|0., 2|0., 3|0., 4|0., 5|0., \cdot 6|0.2, 7|0.3, 8|0.7, 9|0.8, 10|1.0]. \quad (11)$$

It should be noted that these definitions are provided by the user or the system designer based on his understanding of the linguistic variables. If it is defined by the system designer, the assumption is that these definitions correspond in some way with the user's intuitive meaning for the terms, or a high correlation exists between the designer's fuzzy definitions and the user's intuitions.

B. Fuzzy Set Evaluation of Risk

The second part of our model evaluates the risk of an entire system based on the fuzzy estimate of the risk components. The model allows the user to provide a fuzzy estimate of the probability of occurrence and severity of loss of the lower components of risk. Then the uncertainty values of the lower levels are composed to generate the risk value of a higher level using the concepts of fuzzy set theory. These risk values are then combined with the fuzzy weighted factors of each component until all risk components are considered and the total risk is evaluated.

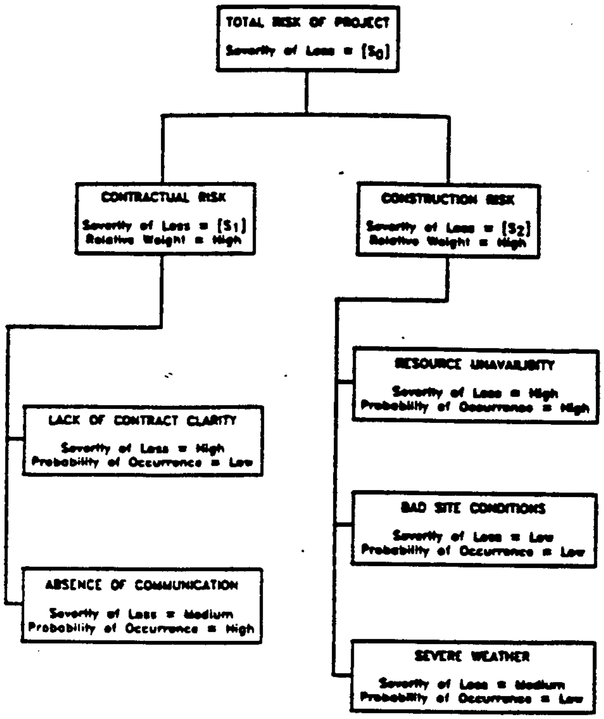

Fig. 3. Structure of risk analysis.

Consider the simple risk analysis model for a construction project as shown in Fig. 3. It is assumed that the overall risk of a project can be divided into two major components: contractual risk and construction risk [14]. Examples of contractual risk are lack of contract clarity, absence of communication between the parties, and problems of timeliness in contract administration. Construction risk is risk inherent in the work itself and would be present even if one company with perfect internal communication performed all of the functions itself. This figure is not intended to be a complete list of uncertainty factors and readers are referred to [14] and [24] for a more comprehensive risk management breakdown structure.

As Fig. 3 indicates, each component is further divided into subdivisions. The model user first provides the linguistic variables which describe the "severity of loss" and "probability of occurrence" at the lowest level of the decision tree. To illustrate, Fig. 3 shows there is a "low" probability of lack of contract clarity along with a "high" severity of loss if such an uncertainty occurs. Assume that these linguistic variables are designated as: high $[H]$; medium $[M]$; and low $[L]$ which are defined in a form similar to (2).

Now, using a fuzzy set mathematical model developed by Zadeh, it is possible to evaluate the severity of loss at the next higher level as follows:

$$[R] = \frac{\sum_i [W_i] \odot [R_i]}{\sum_i [W_i]}, \qquad i = 1 \text{ to } n \qquad (12)$$

in which $[R]$ = a fuzzy set which represents the fuzzy risk value of a higher level; n = total number of components; $[W_i]$ = fuzzy weight factor of lower level of component i; and $[R_i]$ = fuzzy risk value of lower level of component i.

This equation uses the Zadeh's extension principle for extending functions over the integers to functions over fuzzy subsets based over the integers. The method of evaluation was described in (6), (7), and (8).

In the case of Fig. 3, the severity of loss of contractual risk $[S_1]$ can be estimated by the following representation of (12):

$$[S_1] = \frac{\{[H] \odot [L]\} \bullet \{[M] \odot [H]\}}{[H] \bullet [L]}. \qquad (13)$$

Then the relative weight factors for the next higher level must be identified. For example, in this instance both contractual and construction risks are highly important from the decision maker's viewpoint. Again using (12), the overall severity of loss $[S_0]$ can be calculated. This fuzzy set $[S_0]$ shows the overall risk of this project based on the assumed uncertainty factors. Next, this fuzzy set must be translated back to a linguistic variable describing the risk in a word such as "high" or "low." The following section describes this process.

C. Linguistic Approximation

The objective of this part is to find an appropriate natural language expression for the estimated fuzzy set $[S]$. There are basically three techniques: 1) Euclidean distance; 2) successive approximation; and 3) piecewise decomposition.

The Euclidean method is usually applied when the set of natural language expressions is small. It calculates the Euclidean distance from the given fuzzy set to each of the fuzzy sets representing the natural language expressions. The distance between fuzzy set X (unknown), and fuzzy set A (known) can be calculated as follows:

$$d(X, A) = \left\{ \sum_i [X(i) - A(i)]^2 \right\}^{1/2}, \qquad i = 1 \text{ to } n \quad (14)$$

in which d = Euclidean distance between two fuzzy sets; i = an integer between 1 and n; n = an integer that defines the highest value of the fuzzy set universe [11]. The application of (14) is shown in the illustrative example below.

The successive approximation method is applied when the set is large. This method assumes two close primary terms, then various expressions are applied to these two points in order to approximate the closest natural language expression [6], [19]. The piecewise decomposition method divides the linguistic variables into intervals. Then each interval is combined with one of the standard logical connectives to approximate the natural expression [17].

The last two methods are difficult to implement, and it is recommended that the Euclidean distance method be utilized. The proposed model is developed based on the first technique which identifies the closest natural expression by minimizing the Euclidean distance.

VI. An Illustrative Example

This example illustrates how the proposed model can be implemented numerically. The first step is to identify and classify the forecasted possible major uncertainty in a decision tree format as shown in Fig. 3. The next step is to identify the natural language expressions and the fuzzy sets describing them. It is not feasible to perform the calculations by hand if the universe over which fuzzy sets are defined is large. Many fuzzy set applications are done in APL (a programming language), which allows very flexible vector manipulations and in particular allows vectors to grow in length [5], [10]. In this example for purpose of illustration, the x scale is limited to values of 0, 1, 2, and 3. The following expressions are assumed:

$$\text{Low} = [L] = [0|1.0, 1|0.6, 2|0.2, 3|0.0] \tag{15}$$

$$\text{Medium} = [M] = [0|0.3, 1|1.0, 2|1.0, 3|0.3] \tag{16}$$

$$\text{High} = [H] = [0|0.0, 1|0.2, 2|0.6, 3|1.0]. \tag{17}$$

$$[H]\odot[H] = [1|0.2, 2|0.2, 3|0.2, 4|0.6, \cdot 5|0.6, 6|0.6, 7|0.74, 8|0.87, 9|1.0]. \tag{27}$$

Next the fuzzy values of $[S_1]$ and $[S_2]$ can be calculated from (18) and (19) as:

$$[S_1] = [0|0.3, 1|1.0, 2|1.0, 3|0.6] \tag{28}$$

$$[S_2] = [0|0.0, 1|1.0, 2|0.67, 3|0.34]. \tag{29}$$

Then the total risk can be estimated:

$$[S] = \frac{\{[S_1]\odot[H]\} \bullet \{[S_2]\odot[M]\}}{[H]\bullet[M]} \tag{30}$$

$$[S] = \frac{[1|0.3, 1|0.45, 2|0.6, 3|1.0, 4|1.0, 5|1.0, 6|1.0, 7|0.87, 8|0.73, 9|0.6]}{[1|0.2, 2|0.3, 3|0.6, 4|1.0, 5|1.0, 6|0.3]} = [0|0.3, 1|1.0, 2|0.73, 3|0.6]. \tag{31}$$

Next, the user provides the severity of loss and probability of occurrence of the lowest level of the tree diagram as shown in Fig. 3. Now, the severity of loss of higher levels (i.e., construction risk and contractual risk) can be estimated as follows:

$$[S_1] = \frac{\{[H]\odot[L]\} \bullet \{[M]\odot[H]\}}{[H]\bullet[L]} \tag{18}$$

$$[S_2] = \frac{\{[M]\odot[L]\} \bullet \{[L]\odot[L]\} \bullet \{[H]\odot[H]\}}{[L]\bullet[L]\bullet[H]}. \tag{19}$$

The components of (18) and (19) can be evaluated based on (6), (7), and (8) using the concepts of normalization and convexity. A fuzzy set is normalized by adjusting the degree of membership of the elements so that at least one element has the value of one in the set. The concept of convexity means adjusting the membership values upward, if necessary, to insure a relatively smooth curve and to avoid any discontinuities. Applying (6) and (7) for addition and multiplication:

$$[L]\bullet[H] = [1|0.2, 2|0.6, 3|1.0, 4|0.6, 5|0.2] \tag{20}$$

$$[L]\bullet\{[L]\bullet[H]\} = [2|0.2, 3|0.2, \cdot 4|0.6, 6|1.0, 7|0.6, 8|0.2] \tag{21}$$

$$[H]\bullet[M] = [1|0.2, 2|0.3, 3|0.6, 4|1.0, 5|1.0, 6|0.3] \tag{22}$$

$$[H]\odot[L] = [0|1.0, 1|0.8, 2|0.6, \cdot 3|0.6, 4|0.2, 5|0.2, 6|0.2] \tag{23}$$

$$[M]\odot[H] = [0|0.3, 1|0.45, 2|0.6, 3|1.0, \cdot 4|1.0, 5|1.0, 6|1.0, 7|0.77, 8|0.54, 9|0.3] \tag{24}$$

$$[M]\odot[L] = [0|1.0, 1|0.6, 2|0.6, \cdot 3|0.3, 4|0.2, 5|0.2, 6|0.2] \tag{25}$$

$$[L]\odot[L] = [0|1.0, 1|0.6, 2|0.2, 3|0.2, 4|0.2] \tag{26}$$

Now, the fuzzy expression represented by (31) must be translated back to a linguistic variable. Applying (14), the Euclidean distance between fuzzy set $[S]$ and the predefined fuzzy sets (low, medium, and high) can be estimated:

$$d(S, \text{Low}) = [(0.3-1.0)^2 + (1.0-0.6)^2 + (0.73-0.2)^2 + (0.6-0.0)^2]^{1/2} = 1.14 \tag{32}$$

$$d(S, \text{Medium}) = [(0.3-0.3)^2 + (1.0-1.0)^2 + (0.73-1.0)^2 + (0.6-0.3)^2]^{1/2} = 0.40 \tag{33}$$

$$d(S, \text{High}) = [(0.3-0.0)^2 + (1.0-0.2)^2 + (0.73-0.6)^2 + (0.6-1.0)^2]^{1/2} = 0.95. \tag{34}$$

Among the three predefined fuzzy sets, the set "medium" has the closest Euclidean distance to the fuzzy set $[S]$. Therefore the total risk of this project is "medium." More accuracy might be introduced in several ways. One way might be to increase the number of linguistic variables (i.e., very low, low, medium, fairly high, and high). Another way might be to increase the universe of the fuzzy sets from four, in this illustration, to ten, for example.

VII. Conclusions

Although the above example of the use of fuzzy sets is relatively straightforward, the practical application of fuzzy set theory in construction risk analysis is still in the research stage and more work is needed in this area in order to develop a practical risk assessment model. One problem is how to assign the membership values of a fuzzy set to represent a linguistic variable. Since this is the starting point for any fuzzy set analysis, it is obviously important for the membership values to be as realistic as possible. Additionally, it may be valuable for the user to do sensitivity analysis on selected fuzzy sets to determine the impact of varying the membership values. References [3], [4], and [9] provide methodologies to resolve some of these difficulties.

Another problem in fuzzy set analysis is how to perform arithmetic operations. Although extensive research has been done to develop the basic concepts of fuzzy set theory, it often happens that individual practitioners have their own intuitive notions about how concepts of arithmetic should be applied. More research is needed in order to standardize arithmetic operations.

There is also the problem of how to associate the final fuzzy set in a series of calculations with a linguistic variable. A generally used technique and the one described in this paper involves calculating the Euclidean distance between the fuzzy set under question and a set of benchmark fuzzy sets. The The fuzzy set under question thus takes on the linguistic characteristic of the closest of the benchmark fuzzy sets.

Although additional work needs to be done to make the use of fuzzy sets more generally acceptable, they could allow an analyst to deal with many of the uncertainties involved in project risk analysis. Fuzzy set theory might then constitute the basis for linguistic analysis and resolve some of the difficulties of traditional models. This paper has presented a framework in which fuzzy sets might be used for risk analysis.

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Appendix 4

A Brief Description of Other Decision Support Models

Brief Description of Other Decision Support Models

Other decision support systems were carefully investigated for possible implementation in this study. However, due to their inherent weaknesses, they were not found to be suitable. The following section briefly describes these systems and their major weaknesses.

1. Rate of return on investment analysis

The rate of return a uses a net cash flow diagram based on costs and revenues to estimate the internal rate of return. This method is used when accurate cost and revenue data are available. However, in this case such data was not available. This is due to the fact that revenue calculations are more common in private industry than in the military.

Discounted cash-flow analysis makes the following contributions to decision making: an explicit recognition that time has economic values to the corporation, and that near money is more valuable than distant money; recognition that cash flows are what matter, hence capitalization accounting and the resulting book depreciation are irrelevant for capital decisions. For more information see the book by Joel Dean, Managerial Economics, in Handbook of Industrial Engineering and Management 2nd ed., W. G. Ireson and E. L. Grant, eds. Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1971.

2. Net present value analysis

Net present value analysis uses the same concept as rate of return analysis. A net cash flow must be developed first, and then present value of the net cash flow is estimated. The model requires an estimate of the required rate of return which is extremely difficult to quantify for this case. Therefore, this model was not considered suitable.

Two uses of net present worth calculations in decision making are: comparison of alternative series of estimated money receipts and disbursements; and assessment of valuation on prospective net money receipts. A third important use of present worth is for trail and-error calculations to determine unknown rates of interest or return. Because calculation of present worth is often called discounting, writers on economics often refer to an interest rate used in present worth calculations as a discount rate. For further information, the readers are referred to Paul T. Norton, Handbook of Industrial Engineering and Management, Engineering Economy, W. G. Ireson, and E. L. Grant, eds., Englewood Cliffs, N.J.: Prentice Hall, Inc., 1971.

3. *Pay back period analysis*

This method calculates the time period required to recover the initial investment. If the investment continues beyond that point, then it becomes profitable. This method disregards the time value of money. This method is not applicable in this study.

The pay back period analysis method is normally applied in small enterprises to use some variant of the payout (or payback) period as the primary criterion to compare the merits of proposed investments, particularly when the comparisons are made at the level of capital budgeting. Some large enterprises also base decisions on comparisons of payout periods. Except for the special case where funds are so limited that no outlay can be made unless the money can be recovered in an extremely short time, the payout period is never an appropriate way to compare a group of proposed investments. The objection is that the payout period fails to give weight to the difference in consequences of different investment proposals after the date of the payout. Clearly it would not be superior to a proposal for a new production machine having a longer payout period, say 4 years, but favorable enough consequences for many years thereafter to give it an overall rate of return. Some analysts have attempted to correct the foregoing bias of crude payout in favor of short-lived alternatives, modify the payout calculation by computing so-called payout after depreciation, or sometimes after both depreciation and interest. Such modified payout figures are meaningless as they involve a double counting of the first cost of plant. There are, in fact, many variants of the payout method in use in industry, none of them providing a sound basis for comparing investment proposals. For further information see the Principles of Engineering Economy by Grant, Ireson, and Leavenworth published by Wiley, 1982.

4. *Utility theory*

The utility theory uses a set of curves known as utility curves which best describe the decision makers satisfaction. These utility curves are developed based on interview with experts. However, these utility curves may change by time and other factors. This method was not suitable for this case since it was difficult to develop the utility curves for all the factors listed in the table. Therefore the Utility Theory model would have yielded inaccurate results in for this syudy.

The fact that different persons have quite different attitudes toward risk has led certain theorists to hunt for ways to quantify such attitudes. Utility theory provides one approach. Simply stated, utility theory attempts to quantify an individual's preference among alternatives in risk situations. Utility is measured on an arbitrary scale of units called "utiles." The relationship between utility and dollars may be determined for an individual by asking an appropriately designed set of questions. A plot of the individual's responses to these questions is the utility function for that individual. In any choice between risky alternatives, the theory assumes that an individual decision maker will choose the alternative that maximizes utility. Thus, given knowledge of the utility function, the probabilities associated with possible outcomes, and the monetary consequences of each outcome, an analyst should be able to predict the decision maker's choice. For further information, the reader is referred to John von Neumann and Oskar Morgenstern, Theory of Games and Economic Behavior (Princeton, N.J.: Princeton University Press), or the article by Ralph O. Swalm, "Utility Theory—Insights Into Risk Taking," Harvard Business Review (November-December 1966).

5. Neural network

The neural network uses the same concept as the human mind to select between alternatives. First, a network must be trained by using a set of existing data. After the training, then the network can be used for future forecasting. This method was not suitable for this study since a network based on such a large amount of data was not available.

Neural networks are used when the amount of data being stored in a computer system is reaching an unmanageable level. However, access to corporate data is critical to implementing effective business procedures and maintaining a competitive edge. Neural networks provide a new way to cope with huge amounts of data. Neural computing is based on the neural network, which is modeled after the human brain. Neural computers differ from conventional computers in that the neural machines are capable of learning, while conventional computers must be explicitly programmed for each step or problem. The financial sector has been using neural technology for risk management, and other companies are using it for decision support.

Neural networks can be used by programmers to recognize patterns and solve problems. A good neural network can be programmed to solve a wide range of problems, but programmers often neglect to effectively use them. A neural network contains several layers of nodes, which enables the solving of larger problems. These neural networks also include multiple outputs, which provide multiple output classes. Before programmers deploy a neural network, they must put the system through a training period, which is basically an iterative process that defines the weight of each node. For backpropagation neural networks, the training process propagates errors back through the network. For more information see the paper written by Enticknap, Nicholas titled Knowledge is the key, in the Computer Weekly journal, Nov. 30,1995.

6. Knowledge based expert systems

This system is based on the knowledge collected from an expert. It shows the line of reasoning by a professional. The system might be based on production rules which consist of a set of IF-THEN rules. However, for this study, there were not sufficient patterns for the EOD and hazardous remediation operations to establish sound IF-THEN rules. Therefore, the knowledge based expert system was not considered for implementation.

Knowledge based expert systems attack problems for which no general algorithm is known, and there is no known sequence of steps guaranteed to lead to the solution. Comparison of data processing and knowledge engineering shows that data processing is based on algorithmic, repetitive processes, and effective manipulation of large data bases; whereas expert systems are based on heuristics, and effective manipulation of large knowledge bases. This knowledge consists largely of rules of thumb or heuristics. Heuristics enable the human expert to make educated guesses when necessary, to deal effectively with erroneous or incomplete data. Knowledge engineering may be viewed simply as a technique for formalizing common sense heuristic solutions into an understandable and computationally practicable form.

An expert system consists primarily of a set of condition-action rules and operates in cycles. During each cycle, the conditions of each rule are matched against the current state of facts. When rules and conditions match, actions are taken. Those actions affect the current state of facts, making new rules match. A knowledge-based expert system consists of the following components:

Knowledge base: The knowledge base is that portion of a knowledge system that consists of the facts and heuristics about a domain. A knowledge system is a computer program that uses knowledge and inference procedures to solve difficult problems.

Knowledge manager: The knowledge manager uses the information contained in the knowledge base to interpret the current contextual data. It consists or four parts: interpreter, control structure, inference engine, and explanation module which provides the system with the capability of explaining its reasoning.

Knowledge acquisition: Knowledge acquisition is the process of extracting, structuring, and organizing knowledge from experts, so it can be used in a program. There are several stages in knowledge acquisition: 1) Identification stage, which consists of determining the important features of the problem, such as identifying the type and scope of problem, the required resources, and the goals or objectives of the expert system; 2) Conceptualization stage, which consists of defining concepts, relations, control systems, strategies, and constraints related to the problem; 3) Formalization stage, which involves expressing the key concepts and relations in some formal way, usually within a framework suggested by an expert; 4) Implementation stage, which includes formalizing knowledge into a working program which requires content, form, and integration of pieces of knowledge to eliminate global mismatches between data structures and rule of control specifications; 5) Testing stage, which involves evaluating the performance and utility of the prototype and revising it as necessary. For further information see "A Bibliography on Knowledge-based Expert Systems in Engineering," by D. Sriram at CECRL, SIGART, published by Carnegie-Mellon University, 1984.

7. *Probability models*

These models use the concept of probability theory to evaluate the probability associated with each outcome in a decision making process. The model requires a large number of data to develop a distribution curve which could be used for future forecasting. However, the model was not applicable to this case since such a large number of data was not available.

Probability may be thought of as relative frequency in the long run. This may be phrased somewhat more precisely as: assume that if a large number of trials is made under the same essential conditions, the ratio of the number of trials in which a certain event happens, to the total number of trials, will approach a limit as the total number of trials is indefinitely increased. This limit is called the probability that the event will happen under these conditions. It should be noted that this limit is always a fraction (or decimal fraction), which may vary from 0 to 1. A probability of 0 corresponds to an event that never happens under the described conditions; a probability of 1 corresponds to an event that always happens. It is because probability describes relative frequency in the long run that the concept is useful in practical affairs. But its use would be severely limited if the only way to estimate any probability were by a long series of experiments. For further information see the Principles of Engineering Economy by Grant, Ireson, and Leavenworth published by Wiley, 1982.